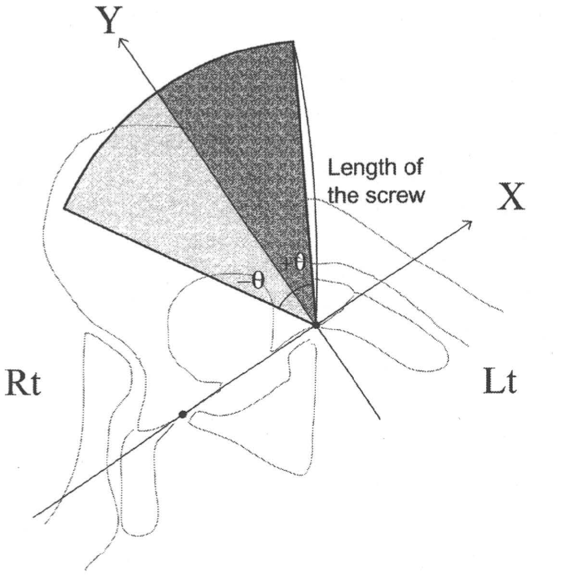

Fig. 2 The expected area of the pedicle screw. We simulated the pedicle screw placement with some direction error (±θ) and the variable length (length of the screw) with sensitivity analysis. We defined a warning pedicle as that when the aorta enters this zone

parameters and the *X*-and *Y*-unit of the left pedicle–aorta line at the apex were calculated.

Results

The relative position of the aorta to the spine changed dramatically at the thoracic spine (Table 1; Fig. 3). The left pedicle-aorta angle spanned from −46° to 78° (average 29.7°) at the thoracic spine and from −38° to 13° (average −16.3°) at the lumbar spine; the left pedicle–

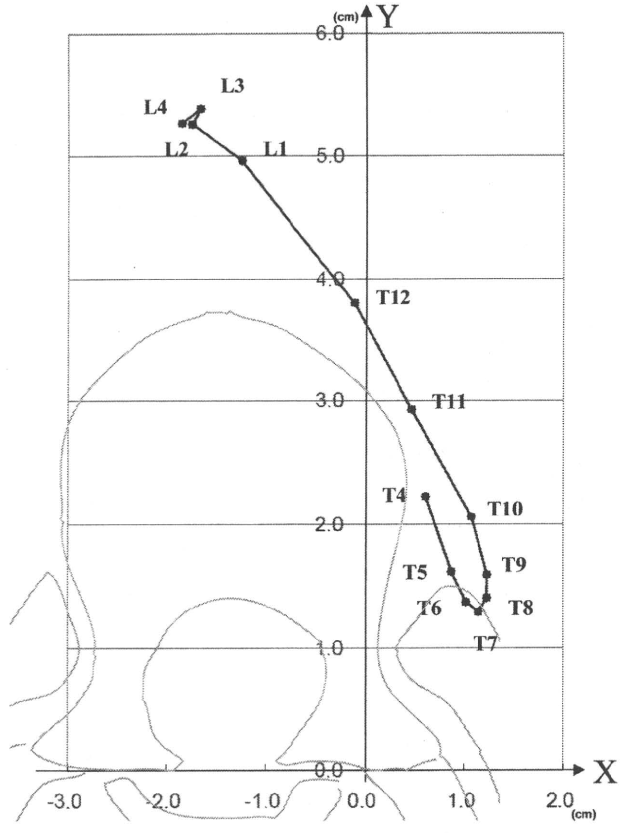

Fig. 3 The average course of the aorta relative to the spine. The origin is set at the middle of the base of the left superior facet. A line joining the middle points of both bases of the superior facets is defined as *X*-axis. The aorta begins to be seen from T4. It descends laterally and posteriorly and turns back at T7. At T12, the aorta is in front of the left pedicle and moves to the right side at the lumbar level. Attention should be paid to the spine drawn in the figure, because the size of the spine changed considerably at the level of the spine

Table 1 Distribution of the left pedicle-aorta angle, the left pedicle-aorta distance, and the pedicular line-aorta distance

	Left pedicle–aorta angle (°)	Left pedicle–aorta distance (mm)	The pedicular line–aorta distance (mm)
T4	20.1 ± 22.7	24.5 ± 6.2	20.9 ± 9.7
T5	32.1 ± 20.3	19.4 ± 4.4	14.1 ± 8.5
T6	39.5 ± 17.3	17.8 ± 3.5	10.9 ± 7.2
T7	43.8 ± 13.6	17.6 ± 3.6	10.1 ± 6.3
T8	42.8 ± 11.9	19.0 ± 4.2	11.4 ± 6.5
T9	40.0 ± 12.8	20.6 ± 4.9	13.6 ± 7.2
T10	30.2 ± 15.1	24.0 ± 6.4	19.2 ± 8.6
T11	13.0 ± 19.9	31.5 ± 8.1	29.1 ± 11.0
T12	0.3 ± 15.6	39.3 ± 8.3	36.9 ± 8.4
L1	-12.9 ± 13.3	52.4 ± 7.1	48.3 ± 7.0
L2	-17.7 ± 10.3	56.2 ± 6.2	51.2 ± 5.2
L3	-16.9 ± 6.8	56.7 ± 5.4	52.9 ± 4.2
L4	-19.4 ± 5.0	56.0 ± 5.0	52.4 ± 7.4

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.

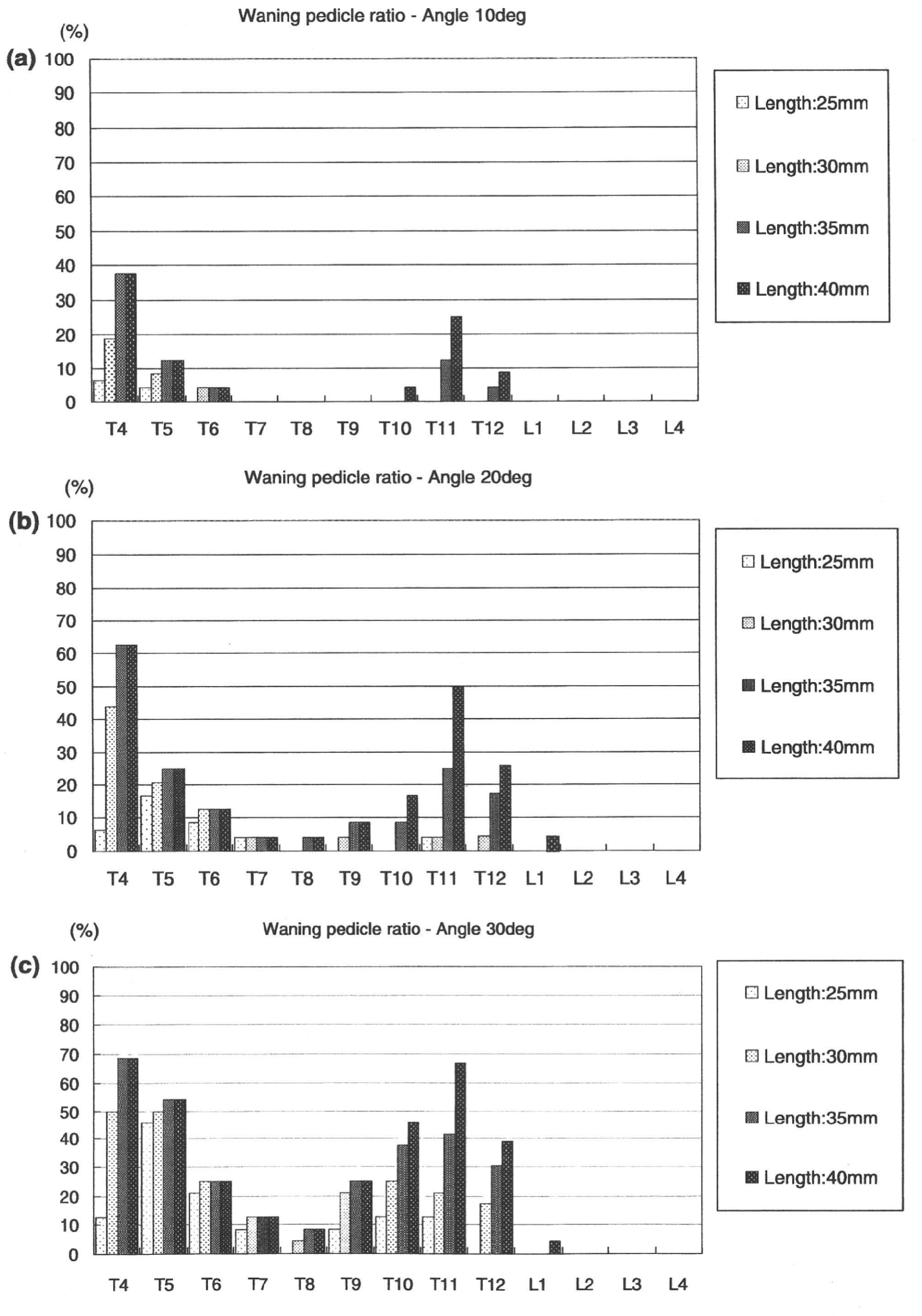

Fig. 4 Distribution of warning pedicle ratios from T4 to L4 in 12 scenario. In any scenario, there was a high percentage of warning pedicles at the thoracic spine except at T7 and T8. **a** The warning pedicle ratio when the direction error is within 10° and the screw length changes from 25 to 40 mm.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

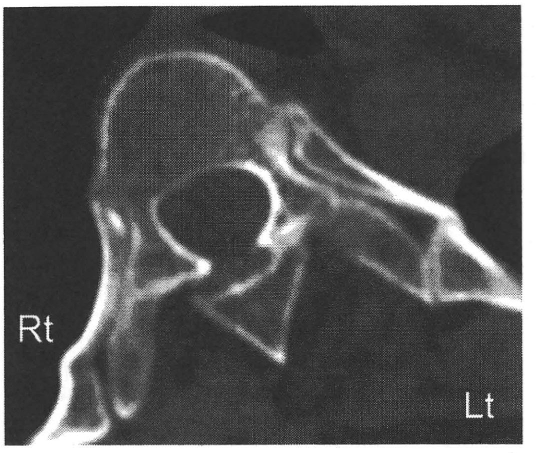

Fig. 5 A case with a typical position of the aorta around the apex level. Though a distance to the left base of the superior facet (an insertion point of a pedicle screw) is closer than other levels, the aorta often resides in the most lateral position from the spine and allows wider maldirection of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

圧迫性頚髄症の痛みとしびれ

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中原進之介　　松本　嘉寛　　清水　克時
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シンポジウム SYMPOSIUM ■四肢のしびれ感

圧迫性頸髄症の痛みとしびれ

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Pain and Numbness in Cervical Stenotic Myelopathy

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臨整外 45：683～687，2010

Key words：しびれ(numbness)，痛み(pain)，後縦靱帯骨化症(ossification of posterior longitudinal ligament)，頸椎症性脊髄症(cervical spondylotic myelopathy)，患者報告アウトカム(patient reported outcome)

多施設横断研究により圧迫性脊髄症の痛み・しびれに関する調査を行った．後縦靱帯骨化症と頸椎症性脊髄症288名と健常者に患者背景，画像とともにquality of life(QOL)・頸椎関連・心理ストレス・痛みとしびれを調査した．治療内容によらず健常者に比しすべてのアウトカムが低下していた．活動制限を生じる痛みが保存治療で10%，手術治療で15%にみられた．痛みは腰・頸部，しびれは四肢が強く，numerical rating scale(NRS)5以上の頸部痛が36%，上肢しびれが41%にみられた．上肢しびれは四肢・体幹機能や心理ストレスと関連があり，満足度と相関していた．

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この研究は厚生労働科学研究費(研究課題：脊柱靱帯骨化症に関する調査研究)の助成を受けて行われた．

はじめに

脊椎外科医は圧迫性脊髄症に対して麻痺の改善を第一の治療目標としてきた．ところが手術後も脊椎の痛みや四肢のしびれがしばしば残存し，麻痺の改善にもかかわらず痛み・しびれを強く訴える患者に遭遇する．しかし過去の研究は運動障害とその回復に関心が寄せられてきたため，こうした痛み・しびれに対して焦点を当てた研究は多くはない．本研究の目的は圧迫性脊髄症患者の実態を把握し，痛み・しびれの患者へのインパクトを解析することである

対象・方法

本研究は厚生労働省難治克服事業脊柱靱帯骨化症の多施設研究として21の大学病院とその関連施設で行われた．調査期間は2006年7月から2007年11月である．対象は頚椎後縦靱帯骨化症(OPLL)と頚椎症性脊髄症(CSM)で，保存治療・手術治療ならびに対照として調査した健常者の計3群を比較した．

調査内容は患者背景と疾患・治療内容，画像情報，患者報告アウトカムの3つである．

患者背景として年齢・性別・感覚障害出現から現在(あるいは手術)までの期間・運動障害出現から現在(あるいは手術)までの期間，手術症例では手術アプローチを，画像情報としてX線像での脊柱管前後径，MRIでのT2高輝度の有無と頭尾側方向の長さである．患者アウトカムとして，

1) 包括的調査票としてSF-8[3]の8つのドメイン，
2) 頚椎症あるいは頚髄症調査票として日本整形外科学会頚部脊髄症治療成績判定基準JOACMEQ[4]，医師評価である日本整形外科学会頚椎疾患治療成績判定基準(旧JOAスコア)，頚椎症尺度であるneck disability index(NDI)[5]を，
3) 脊柱の可とう性評価として作成し前屈時指床距離(finger floor distance)と相関のあるself-assessment bending scale(SABS)[1]を，
4) 心理評価として日本語POMS短縮版(profile of mood states)[8]を用いた．30の質問からなり，緊張・抑うつ・怒り・活気・疲労・混乱の6因子が同時に測定できる質問票である．

痛みとしびれの評価としては，痛み評価ではchronic pain grade(CPG)と，身体部位別(頚部・頭部・背部・上肢・腰部・下肢の6つ)の11段階による痛みおよびしびれ強度(numerical rating scale : NRS)を調査した．CPGはグレード0から4までであり，高いほど障害が強い．またCPGの質問票から疼痛強度も算出し比較した．

さらに，上肢しびれに関連する因子の検索と，満足度との関連を解析した．

結果

1. アウトカム

調査総数は350名で，内訳はOPLLの保存治療80名，OPLLの手術治療104名，CSMの保存治療53名，CSMの手術治療69名，健常者44名であった．保存治療，手術治療，健常者の特徴を表1に示す．保存治療，手術治療いずれも男性に多く，平均年齢は60歳代であった．手術治療は前方29例，後方138例，その他6例であった．脊柱管前後径は差がなかったが，保存治療群ではMRIのT2高輝度のない症例が多かった．

1) 患者報告アウトカム

SF-8では健常者に比べて保存治療，手術治療ともすべてのドメイン，特に身体機能が低かった(表2)．保存治療，手術治療に有意な差はなかった．JOACMEQでも健常者に比べてすべてのドメインで保存治療，手術治療とも低かったが，頚椎機能は手術治療群が一段と低かった(表2)．旧JOAスコアでは感覚スコアで上肢と体幹で有意差があるものの，保存治療と手術治療の差はほとんどなかった(表3)．NDIでは保存治療群で29.3±17.5，手術治療群で29.8±18.5で同等であったが，健常者5.6±7.5に比べ有意に高かった($p=0.000$)．

SABS(高値ほどやわらかい)でみる体幹のやわ

表1　患者背景と画像情報

	保存治療	手術治療	健常者
総数	133	173	44
男・女	88・45	124・49	29・15
年齢	67.1±10.1	65.8±9.7	63.9±7.9
罹病期間(年)			
しびれ発症から調査まで	7.3±5.5	10.2±7.0**	
しびれ発症から手術まで		3.2±4.4	
麻痺発症から調査まで	5.0±3.6	8.0±6.0**	
麻痺発症から手術まで		0.9±2.1	
画像			
脊柱管前後径(mm)	13.7±1.7	13.8±2.3	
MRI/T2 高輝度あり	47.3%	63.9%*	
T2 高輝度長さ(椎体)	1.8±0.8	1.6±0.8	

*：p<0.05
**：p<0.01

表2　患者報告アウトカム

	保存治療	手術治療	健常者
SF-8			
全体的健康感	42.3±7.7	45.3±8.1*1	51.1±5.6*2
身体機能	42.7±8.8	43.1±7.9	51.4±3.9*2
日常役割機能(身体)	42.6±9.3	42.7±9.4	51.8±3.6*2
体の痛み	42.4±9.0	43.6±9.4	52.3±6.8*2
活力	46.4±6.7	47.3±7.7	51.9±5.3*2
社会生活機能	43.4±9.4	43.7±9.9	53.0±4.1*2
心の健康	46.3±6.9	47.9±7.1	52.4±4.9*2
日常役割機能(精神)	44.0±10.0	45.6±10.2	52.4±3.0*2
JOACMEQ			
頸椎機能	69.5±28.6	59.2±30.8*3	90.5±17.7*4
上肢機能	83.6±20.0	80.0±19.7	99.0±2.3*4
下肢機能	72.3±27.7	67.2±27.1	97.1±8.2*4
膀胱機能	76.6±19.2	75.6±21.6	91.8±11.3*4
QOL	47.2±18.0	47.8±19.0	68.5±11.6*4

SF-8：健康関連 QOL 尺度
JOACMEQ：日本整形外科学会頚部脊髄症治療成績判定基準
*1：保存治療と比較して p=0.04
*2：保存治療や手術治療と比較して p<0.01
*3：保存治療と比較して p=0.008
*4：保存治療や手術治療と比較して p<0.01

らかさでは保存治療群で 3.8±1.5，手術治療群で 3.9±1.6 と同等で，健常者 4.7±1.5 と比べると有意に体幹が硬かった(p=0.004)．

POMS は健常者と比較すると怒り・敵意を除く 5 因子でストレスが高いことが示されたが，特に緊張・不安，疲労，混乱での感情ストレスが強いことが示された(表 4)．

表3　旧 JOA

	保存治療	手術治療
上肢運動機能	3.2±0.9	3.1±1.0
下肢運動機能	2.9±1.1	2.7±1.1*1
上肢知覚機能	1.2±0.5	1.1±0.6
下肢知覚機能	1.4±0.6	1.5±0.6
体幹知覚機能	1.7±0.5	1.6±0.6
膀胱直腸機能	2.6±0.6	2.5±0.7

*1：p=0.029

2. 痛みとしびれ

CPG はグレード 3 以上が保存治療群で約 10%，手術治療群で 15% を占めており，治療内容によらず活動制限を生じている割合が少なくないことを示す(表 5)．疼痛強度は健常者と比べて保存治療，手術治療群ともに有意に大きかった．

身体別疼痛では頚椎疾患患者への調査にもかかわらず，腰部が保存治療群で 3.7±3.1，手術治療群で 3.8±2.9 と最も高く，次いで頚部(保存治療 3.5±2.9，手術治療 3.2±2.8)と下肢(保存治療 3.3±3.2，手術治療 3.3±3.1)が強かった．頚部の痛みは NRS 5 以上の患者が 36.1% であった．また頭痛が健常者と比べ両群とも強かった(保存治療 1.6±2.2，手術治療 1.5±1.5，健常者 0.6±

表4　Profile of Mood Status(POMS)短縮版

	保存治療	手術治療	健常者
(T得点)			
緊張・不安	48.2±9.6	47.5±10.0	43.2±8.8*3
抑うつ・落ち込み	49.4±9.6	50.1±9.5	45.3±6.8*2
怒り・敵意	47.3±9.0	48.1±9.5	44.9±6.7
活気*1：	41.2±10.1	42.1±9.2	46.2±8.8*2
疲労	48.2±8.7	47.7±9.1	44.0±6.9*3
混乱	51.9±9.3	52.1±9.9	45.8±7.6*3

*1：活気のみ高いスコアほどよい
*2：保存治療や手術治療と比較して $p<0.05$
*3：保存治療や手術治療と比較して $p<0.01$

表5　Chronic Pain Grade(CPG)のグレードと疼痛強度

	保存治療	手術治療	健常者
グレード0	7.5%	11.6%	30.6%
グレード1	45.3%	39.5%	61.1%
グレード2	36.8%	34.0%	8.3%
グレード3以上	10.4%	15.0%	0%
疼痛強度	40.0±29.0	43.4±30.0	18.7±19.0*1

*1：保存治療や手術治療と比較して $p<0.01$

1.2).

身体別しびれでは上肢しびれ(保存治療4.4±3.1, 手術治療3.9±3.2)とともに, 下肢しびれ(保存治療4.1±3.2, 手術治療4.2±3.2)が次に強かった. 上肢しびれはNRS 5以上の患者が41.4%であった.

3. 上肢しびれと関連する因子

上肢しびれと関連する因子を調べると, 保存治療群では上肢機能・下肢機能・頚椎機能, さらに各ストレス因子, SF-8の各因子, SABSと相関があり, 手術治療群ではさらに年齢, 体重, MRIでのT2強調画像での高輝度の有無と相関があった(表6). また満足度との関連では手術群で頚部痛みと相関があった. (Spearman相関係数0.48, $p<0.001$)

表6　上肢しびれと相関のある因子

	保存治療	手術治療
年齢	ns	.185*
体重	ns	−.195*
T2高輝度	ns	.240**
JOA 上肢運動機能	−.327**	−.477**
下肢運動機能	−.397**	−.235**
SABS*1	−.316**	−.301**
JOACMEQ 頚椎機能	−.395**	−.267**
上肢機能	−.511**	−.438**
下肢機能	−.505**	−.316**
膀胱機能	−.387**	−.212*
QOL	−.528**	−.480**
POMS 緊張・不安	.411**	.316**
抑うつ・落ち込み	.260*	.226*
怒り・敵意	.237*	.266**
活気	ns	−.257**
疲労	.475**	.327**
混乱	.299**	.279**
SF−8全体的健康感	−.593**	−.395**
身体機能	−.554**	−.324**
日常役割機能(身体)	−.556**	−.439**
活力	−.444**	−.316**
社会生活機能	−.591**	−.374**
心の健康	−.435**	−.389**
日常役割機能(精神)	−.569**	−.362**

*1：Self-Assessment Bending Scale,
*：$p<0.05$, **：$p<0.01$(Pearson　相関係数), ns：not significant

考察・結語

たとえ早期に治療を行った場合でも感覚神経障害, すなわち痛みやしびれが改善しないことは少なくない. とくに後頚部から肩甲部にかけての痛みと上肢のしびれに対する術後の訴えは多い. 今回の結果では治療の内容によらず, 同程度の頚部の痛みと上肢しびれがあり, NRS 5以上の強度のある患者が頚部痛みで1/3以上, 上肢しびれで約4割もいた.

手術症例に関しては, 後方手術という間接的除圧が多いことや, 神経根への対処が不十分な可能性はある. しかし前方手術による直接除圧でもかなりの患者でしびれを訴え, QOLを悪化させるような感覚神経障害が残ることがある. これらは難治性の術後疼痛やしびれとして扱われてきたが, 近年は神経障害疼痛あるいは脊髄障害性疼痛と呼ばれるようになってきた. 神経障害性疼痛とは病変あるいは疾患が感覚神経への直接的影響により生じる疼痛, と定義されている[6]. その本態は

maladaptive plasticity，すなわち障害に対する知覚神経の誤った可塑反応と考えられており[2]，障害原因がない状態や生理的な軽度の刺激でもQOL障害につながる痛みが起きている病態である．神経障害性疼痛は整形外科医が得意な侵害受容性疼痛とは異なる病態であり，非ステロイド性抗炎症薬の効果も限定的であると言われている．神経障害性疼痛には異なった治療戦略で取り組む姿勢が求められるであろう．

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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

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

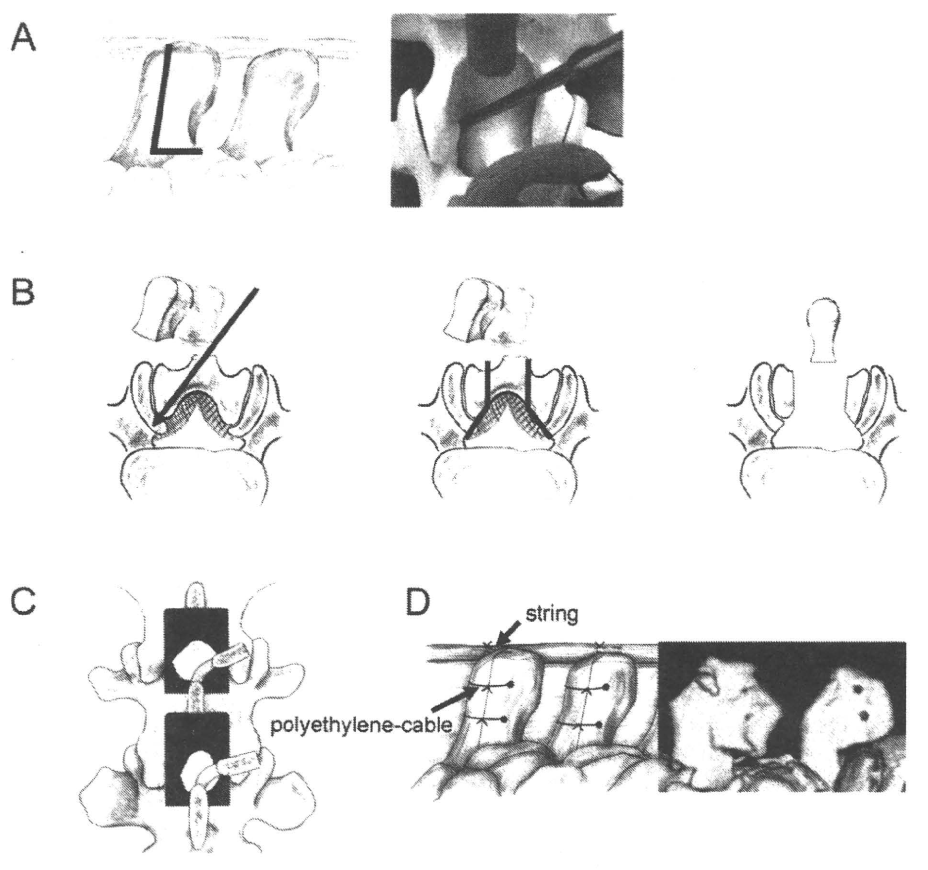

Fig. 1. Illustrations of surgical technique for MFRS. A: Spinous process is cut in an L shape and caudally reflected. B: Temporal spinotomy allows easy access to spinal canal including lateral recesses and makes it easy to perform a trumpet-style decompression. C: Spinotomy and laminotomy can be repeated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

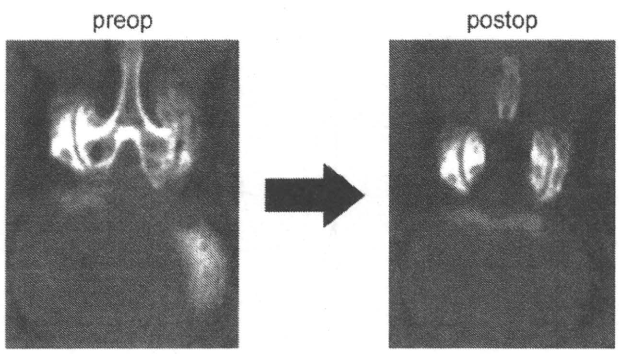

FIG. 2. Preoperative *(left)* and postoperative *(right)* CT scans. *Left:* Preoperative CT shows severe spinal stenosis with narrow and steep facet joints. *Right:* Postoperative CT shows a sufficient trumpeted decompression of the spinal canal with preservation of the facet joints.

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.

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

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.

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-

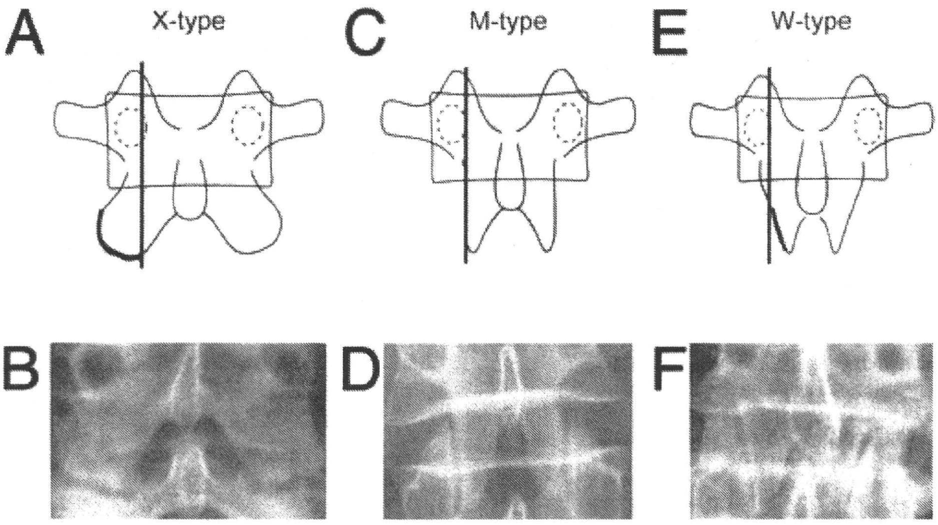

FIG. 3. Schematic drawings and radiographs illustrating the assessment of the shape of inferior facets proposed by Tsunoda. X-type: An outer border of an inferior facet is located outside of a vertical line passing the medial edge of a pedicle. M-type: An outer border of an inferior facet is located 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/≥ 75 years), sex, number of levels decompressed (< 3 levels/≥ 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/≥ 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

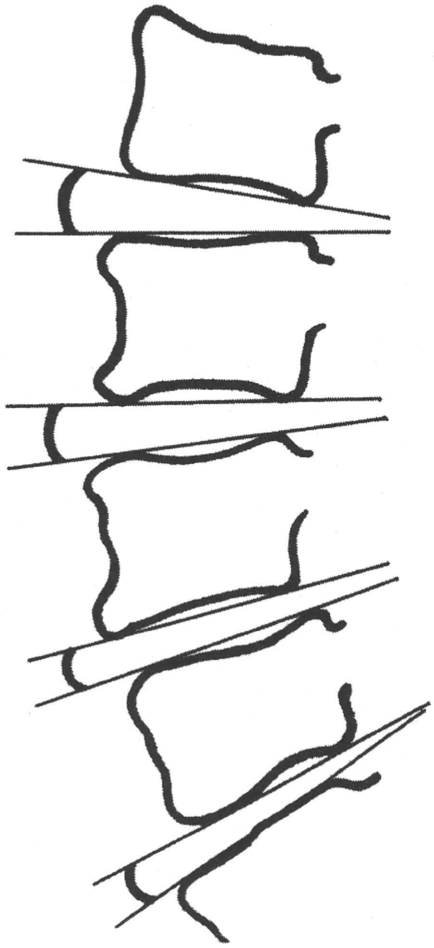

FIG. 4. Schematic illustration of radiographic measurements for segmental sagittal alignment. Segmental sagittal alignment was defined as the angle between the inferior margin of the superior vertebra and the superior margin of the inferior vertebra on neutral position in a lateral radiograph. This angle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

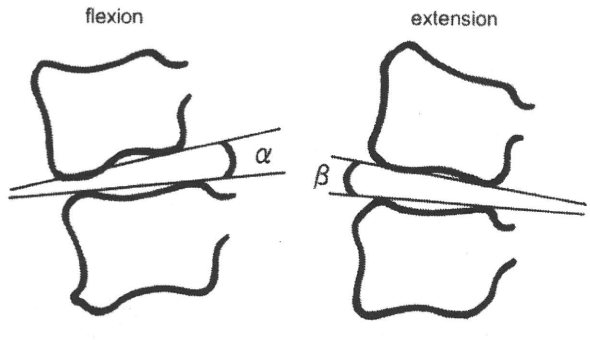

FIG. 5. Schematic illustration of the radiographic measurements for intervertebral range of motion. Intervertebral range of motion was determined on dynamic view as the following: $\alpha - (-\beta)$.

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

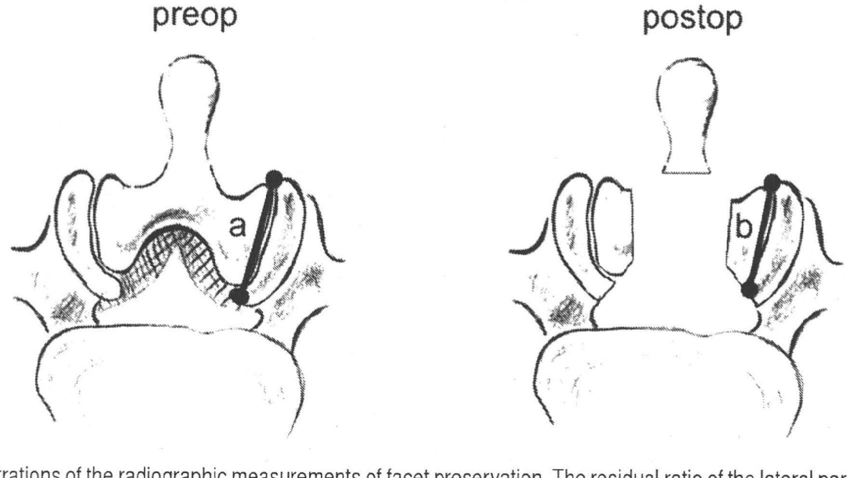

FIG. 6. Illustrations of the radiographic measurements of facet preservation. The residual ratio of the lateral part of a facet joint on CT scans was determined as the following: b/a * 100%

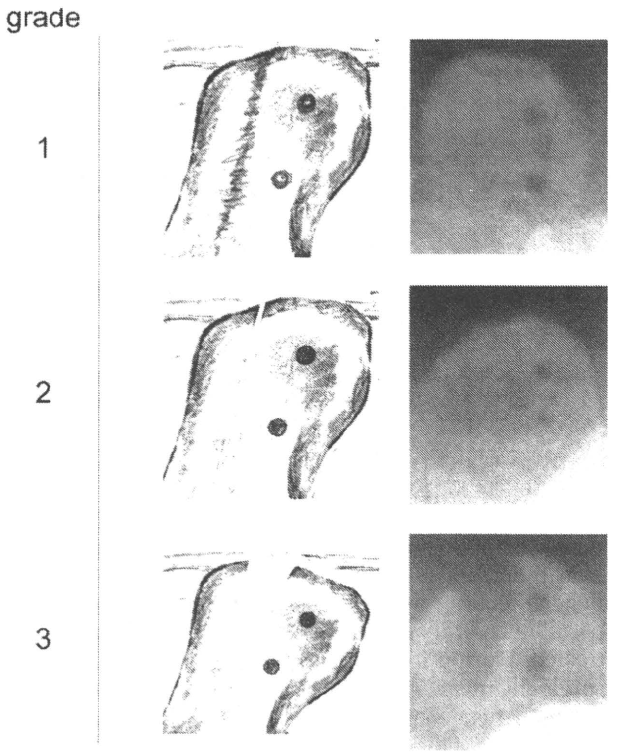

FIG. 7. Evaluation of the union of the reconstructed spinous process on lateral radiographs obtained 2 years after surgery. Grade 1: osseous fusion with no clear zone in the reconstructed area. Grade 2: clear zone opening ≤ 1 mm without increase in flexion views. Grade 3: clear zone > 1 mm, or with increase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

Item (score range)	JOA Score 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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