多孔質人工骨

ハイドロキシアパタイト(hydroxyapatite；HA)は，骨の無機成分のほとんどを占める．このHAを化学的に合成し焼き固めた(焼結)人工骨が，1980年代の半ばに世界に先駆けて国内で実用化された．焼結HAは骨伝導能(後述)を有していることが確認され，さまざまな焼結HA人工骨が開発された．最も一般的な焼結HA人工骨は，周囲骨組織が侵入できるよう，多数の気孔(マクロポア：macropore)を有し，軽石状の多孔体と呼ばれる構造をとる．しかし，従来の多孔質人工骨は孤立した気孔が多く，また焼結HAは生体内でほとんど吸収されないことから，骨組織が表面近くにしか侵入できないことも明らかになった[3]．骨組織が侵入していない気孔は，移植部位の強度を低下させる要因となっていた．近年では，気孔間の連通性を向上させる製法で作製された高連通性の焼結HA人工骨や，極端に気孔率を高めることで高連通性を獲得させた超高気孔率タイプのHA人工骨なども開発され臨床応用されている．

生体吸収性人工骨

破骨細胞は，骨組織に接着した部位にコラゲナーゼなどの酵素を放出するとともに，酸性環境にすることで骨のHAを溶解し骨組織を吸収する．対して，焼結したHAは生体内ではほとんど吸収されない．これは，生体骨のHAはマグネシウムなどの微量の不純物を含み，化学的に溶解されやすいのに対し，合成HAは不純物を含まず結晶性が高いこと，および骨に含まれるHAは微結晶の集合であるのに対し，焼結HAは焼き固められ一塊となっているため，溶解反応の起るHAの表面積が小さくなっているからである(骨組織のHAを角砂糖とすれば焼結HAは氷砂糖)．

近年，HAと同じリン酸カルシウムであるβ-三リン酸カルシウム(β-TCP)製の生体吸収性人工骨も開発された．この多孔質β-TCPは焼結体ではあるが，HAに比較し溶解されやすく，またマイクロポア(micropore)と呼ばれる微小気孔(直

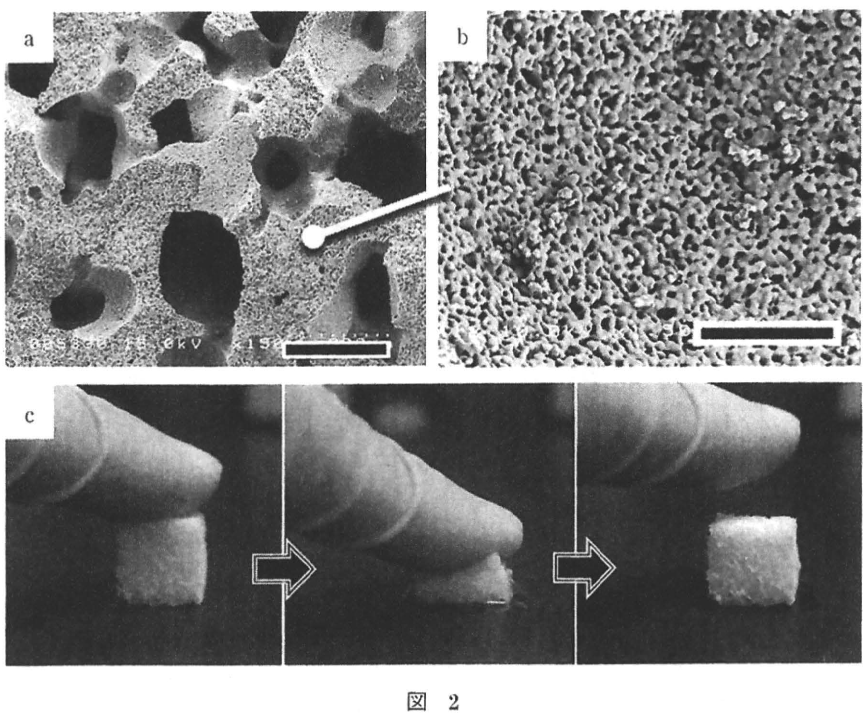

図 2

多孔質β-TCP(オスフェリオン®，オリンパステルモバイオマテリアル)

a：骨組織が侵入しやすいように直径100～400μmの気孔(マクロポア)が多数存在する．スケールバー：200μm

b：aにおける材料実質部には直径数10nm～数μmの微小気孔(マイクロポア)構造が存在する．スケールバー：20μm

c：多孔質ハイドロキシアパタイト・コラーゲン複合体　水分を吸うと，スポンジ状の弾力性を示す．

径数10nm から数μm)が存在するため，表面積も大きい(図2a，b)．骨欠損に移植すると，数ヵ月～数年の間に生体骨に置換されることが確認されている．

さらに新しいタイプの人工骨として，われわれは独立行政法人物質・材料研究機構とともに，多孔質ハイドロキシアパタイト・コラーゲン複合体(HAp/Col)の開発を行っている．この多孔質HAp/Colは，生体骨と同様のナノ構造を有し生体吸収性である．従来の人工骨が非常に脆く崩れやすいのに対し，スポンジ状の弾力性があり操作性に優れている(図2c)．骨伝導能も高く生体吸収性であることが動物実験で確認されており，HOYA株式会社とともに研究開発を進め，現在は臨床治験を実施中である．

人工骨の骨伝導能と骨誘導能

骨伝導能とは，骨組織内もしくは骨欠損に移植した場合，周囲の骨組織からの連続的な骨形成を導く能力のことであり，骨誘導能とは骨以外の組織内に骨組織を形成させる能力である．これまで，人工骨には骨伝導能はあるが骨誘導能はないとされてきた．しかし，多孔質人工骨を動物の筋肉内に移植した近年の研究では，人工骨のなかには弱いながらも骨誘導能をもつものがあることが明らかにされた[4)5)]．この場合，骨形成は多孔質人工骨の内部(マクロポア内)にのみ生じることから，人工骨の骨誘導能には気孔構造の存在が必須であると考えられている．また，骨誘導能が確認されている人工骨に共通しているのはマイクロポアの存在で，同じ材料でもマイクロポアを減少させると骨誘導が起こらなくなることも分かっている．また溶解性の低い純粋なHAよりも，二相性リン酸カルシウムやβ-TCPなどの，ある程度化学的溶解性が高い材料のほうが骨誘導能も高いこともわかっている[4)]．

組織工学的手法

人工骨の骨誘導能の存在が明らかにされたが，その骨誘導は決して高いものではない．そこで組織工学的手法を用いることで，人工骨に骨誘導能を付加する試みが行われている．

1．骨髄間葉系幹細胞(MSCs)

骨髄液中には，多分化能を有するMSCsや前駆細胞が含まれるが数は少なく，巨大な骨欠損の再生に使用するには培養・増殖させる必要がある．培養したMSCsを移植に用いる工程は，培養した細胞を骨形成の足場となる多孔質人工骨内に導入し，足場上で分化誘導を行い移植するというもので，15年以上前に開発され[6)7)]，その後さまざまな研究が重ねられてきた．しかし，培養MSCsは増殖とともに分化能が低下するといった問題や，MSCsの性能を評価する方法が確立されていないといった問題もあり，巨大骨欠損の再建に応用されるまでには至っていない．

2．Bone morphogenetic proteins(BMPs)

BMPsは強力な骨誘導作用を持つ増殖因子で，骨再建への応用が期待されてきたが，普及するに至っていない．最大の要因は，最適なBMP担体が存在しなかったことである．BMP担体に求められる性能はBMPを徐放し，かつ希望する形状の骨組織を形成できることである．これまでに開発された担体の多くは，BMPの放出速度が速いため，骨形成が不十分であったり，逆に十分な骨形成を得ようと過剰な量を使用することで，予定外の部位に骨形成を生じて，合併症を引き起こすという問題を抱えていた．われわれが開発を行っている多孔質HAp/Colは，BMPを吸着する能力が高く，移植を行ってもBMPは容易には放出されない．そのため少量のBMPで骨形成が得られ，また逆に用量を多くしても過剰骨が形成されず，予定通りの形状の骨組織を形成することがで

き，安全性が高い[8]．現在，多孔質HAp/ColもBMPも臨床で使用することはできないが，臨床応用が実現すれば，骨移植における次のブレークスルーになると考えられる．

おわりに

性能向上により骨移植材料における人工骨の割合が増加し続けているだけでなく，社会の高齢化に伴い骨移植全体の件数も増加を続けている．また，組織工学的手法を応用することで自家骨に勝る移植材料も実現されつつあり，これまでにない人工骨の需要を生み出す可能性も期待されることから，人工骨の重要性は今後ますます高まっていくものと考えられる．

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今月のテーマ 表面筋電図

表面筋電計を用いた腰椎変性疾患を有する高齢者の腰背筋活動

Surface electromyography in paraspinal muscle of elderly patients with lumbar degenerative disease

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・表面筋電図を用いて脊椎疾患を有する高齢者に対して立位腰背筋活動および筋疲労が客観的に評価可能であった.
・腰椎後弯症患者は，上位腰椎での筋活動増加と易疲労性が明らかとなった.
・腰椎後弯症患者の腰痛と腰背筋活動の相関が明らかとなり，今後，表面筋電図が治療効果判定として有用である可能性が示唆された.

KEY WORDS 表面筋電図，腰背筋，腰部脊柱管狭窄症，腰椎後弯症

はじめに

近年，運動器不安定症という概念が提唱されている．脊椎圧迫骨折および亀背，高度腰椎後弯・側弯など各種の脊柱変形や大腿骨頸部骨折に代表されるような下肢骨折，骨粗鬆症，変形性関節症，腰部脊柱管狭窄症，神経・筋疾患，長期臥床に伴う運動器廃用などがあげられ，いずれの疾患も適切な予防と対応が急務となっている.

日常診療で脊椎変性疾患に伴う高齢者の腰痛や下肢痛・しびれに遭遇する機会は多い．代表的な脊椎疾患として腰部脊柱管狭窄症があげられる．その名の通り椎間板狭小や変形，黄色靭帯の肥厚によって脊柱管狭窄が起こり神経が圧迫される．特徴的な症状は，下肢痛やしびれによって歩行と休息を繰り返す間欠性跛行である.

一方，腰曲がりに代表される脊椎後弯症は，骨粗鬆症を基盤に発生する老人性亀背や椎間板の変性，背筋不全のため正常な脊椎前弯が失われた状態である．最も直接的な原因は，腰背筋の萎縮とされており，後弯に伴う姿勢不良は，慢性的な腰背部痛の原因となり，その程度が進行するとバランスを失い立位や歩行が困難となり，女性では台所仕事ができない等の日常生活に支障を来すようになる[1].

脊椎後弯変形を矯正するには，内固定金属を用いた脊椎前方固定術や後方固定術が必要であり，手術侵襲が大きい．手術対象としては，比較的若く体力のあるものに限られている.

日常診療では，腰背筋強化運動やコルセットの使用などが選択されており，保存的治療の効果は,

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患者自身の自覚症状に依存することが多い.

当教室では，腰痛患者を対象に積極的に表面筋電計を用いた腰背筋活動の記録を行っている[2]. 腰部脊柱管狭窄症に伴う腰痛や下肢痛，後弯変形による腰痛や易疲労性等に対し，今後の治療や後弯変形の予防のためにも高齢者の腰背筋活動評価が重要となる.

本研究では，60歳以上の脊椎後弯変形を有する患者と腰部脊柱管狭窄症の手術対象患者および健康ボランティアを対象に腰痛の自覚症状についてのアンケートを記入してもらい，ポータブル表面筋電計を用いて腰椎上位および下位レベルでの立位腰背筋筋活動を記録・解析し，各症例の筋活動と腰痛，腰椎アライメントの影響について解析を行った.

対　　象

2008年6月から2009年3月まで当科を受診し，本学倫理委員会承認の説明書により承諾を得た60歳以上の腰椎後弯症患者9名（LDK群；男性4名・女性5名；平均75歳），腰部脊柱管狭窄症患者10名（LCS群；男性5名・女性5名；平均72歳），腰痛歴のない男性ボランティア5名（Vol群；平均62歳）の計24名を対象にした.

方　　法

診察時に問診と身体所見を記録し，JOAスコア（日本整形外科学会腰痛疾患治療成績判定基準：29点満点）の記入を行った．症状，診察所見，画像診断から歩行や立位維持が困難な状況である患者をいわゆる脊椎後弯症とした．腰椎矢状断アライメントで前弯が減少している状態を併せて腰椎後弯症（LDK群）とした．腰痛，下肢痛，しびれが強く間欠性跛行を呈している場合は，画像診断と併せて腰部脊柱管狭窄症（LCS群）とした. LCS群では，日常生活に支障がある手術予定患者を測定した．本人により腰痛VAS（Visual Analogue Scale：100mm）の記入をしてもらった.

画像検査は，立位側面像を用いて腰椎前弯角（L1-S角）を測定した.

ポータブル型筋電計ME3000P（Mega Electronics Ltd. FINLAND）を用いて腰部多裂筋の筋表面筋電図を測定した．第1/2および第4/5腰椎棘突起間レベルで正中より3cm外側，両側の多裂筋直上に表面電極を取り付けて立位安静時に計測した．筋疲労テストには，立位で2kgの錘を両手で1～2分保持してもらいL1/2，4/5レベルで同様に筋活動を記録した．得られたデータは，筋電図解析ソフトMegaWin（Mega Electronics Ltd. FINLAND）を用いて一定時間内での積分筋電図（iEMG）を筋活動量として評価に用いた．錘負荷時の疲労テストでは，一定時間内での平均パワー周波数（MPF）を指標に解析を行った．各例について自覚的評価の腰痛VASおよびJOAスコアを解析して腰痛の有無，程度について分類した．得られた数値の解析には統計解析ソフトGraphPad Prism5（GraphPad Software, Inc.）を用いて3群間の比較にBonferroni's Multiple Comparison Testを使用し$^*p<0.05$を有意差ありとした.

結　　果

1．対象患者データ（表1）

対象患者年齢は，LDK群で高い傾向にあったがLCS群と比較して有意差はなかった．腰痛なしボランティアの平均年齢が62歳と低いのは，腰痛歴の少ない高齢者を探すのが困難なためであった.

JOAスコアは，自覚症状，他覚所見，日常生活動作，膀胱機能を含んだ指標で29点が満点である．JOAスコアは，両群とも手術対象のため低値であった．LDK群のJOAスコアは，LCS群より低いが有意差はなかった．ただし，LDK群の腰痛スコア（◆）は，常に腰痛がある（1点）状況でLCS群より腰痛が強かった．自覚的評価の腰痛VASは，腰痛が最も強い状態を100mmとしている．LDK群で高い傾向にあるがLCS群と

表 1

	年齢	JOA スコア（◆）	腰痛 VAS	L1-S 角
LDK 群（9名）	75±4	11±5.6　(1)	78.8±11.5	8.0±11.9*
LCS 群（10名）	72±5	15±5.2　(2)	55.6±29.4	43.6±14.0
ボランティア Vol 群（5名）	62±2			36.6±10.0

（◆）腰痛スコア　±SD
3　まったく腰痛がない　2　時に軽い腰痛　*p＜0.05
1　常に腰痛　0　常に激しい腰痛

比較して統計学的有意差はなかった．腰椎前弯をしめすL1-S角は，LCS群と比較してLDK群で有意に少なく腰椎後弯を示していた（表1＊）．LCS群と腰痛なし群では有意差を認めなかった．

2．立位安静時の腰背筋筋活動（図1）

被験者に立位安静姿勢を2分間維持してもらい腰背筋活動を記録し，比較的安定した状態の60秒を選択しiEMGを解析した．その結果，LDK群ではL1/2，L4/5レベルでそれぞれ平均 30.4，25.6μV/min，LCS群ではそれぞれ平均17.1，15.8μV/min，腰痛なし群ボランティアではそれぞれ平均13.0，12.4μV/minであった．LDK群で，腰背筋活動が高い傾向にあり，腰痛なし群と比較してL1/2での筋活動が有意に高かった（図1B）．LCS群の筋活動は，腰痛なし群よりも高い傾向にあったが統計学的な差は認められなかった．

3．重錘負荷による脊柱起立筋の筋疲労（図2）

立位で2kgの錘を両手で1～2分保持してもらい筋活動を記録した（図2A）．筋電図が安定した開始30秒から1分30秒の間について疲労解析を行った．LDK群は，L1/2，L4/5両方のレベルで筋疲労を強く認めた．統計学的には，LCS群との差はなく，腰痛なし群と有意差を認めた（図2B）．

4．JOAスコアと腰痛VASと腰背筋活動との関係（図3）

各症例のJOAスコアをX軸，Y軸に立位iEMG値をプロットして回帰直線を作成し，JOAスコアとiEMG値に相関があるか検討した．両群とも明らかな相関関係はなかった（図3A）．次に各症例の腰痛VASを検討するとLDK群ではVAS高値の症例で筋活動が高く，L1/2レベルのiEMG値はVASとの相関を認めた（図3B）．それに対してLCS群では相関を認めなかった．また，筋疲労についてもJOAスコア，腰痛VASとの相関を検討したが，いずれも関係を認めなかった．

5．腰椎前弯角と腰背筋活動の関係

レントゲン矢状断像での腰椎前弯角は，LDK群で減少しており，iEMG値と相関があるか検討した．その結果，腰椎前弯角と筋活動に両群とも明らかな相関は認めなかった．

考　察

本研究では，腰背筋活動量の指標として積分筋電量であるiEMGを用いた．通常，腰痛がない場合に腰背筋の筋放電が最大前屈位になると消失する現象（flexion relaxation phenomenon）を指標にした解析が有名であり，立位姿勢を指標にしたデータは少ない．今回，腰椎後弯症，脊柱管狭窄症，腰痛なしボランティアで立位筋活動を比較・解析した結果，後弯症患者に特徴的な筋活動を得ることができた．図1で示したように立位時L1/2レベルでのiEMGはLDK群のみで高値を示していた．後弯症は，立位時に重心線が前方に移動し立位を維持するのに常に腰背筋活動が必要となる[3]．よってLDK群は，比較的短時間の立位

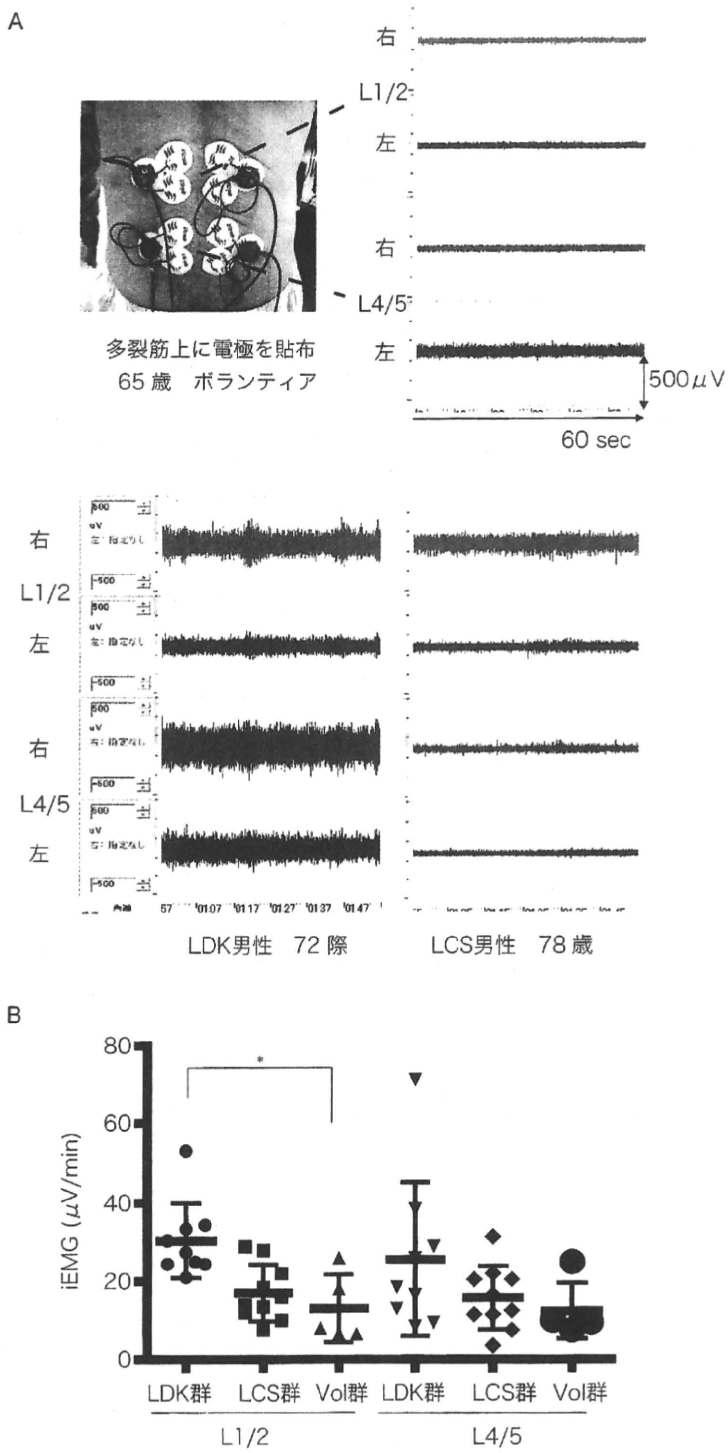

図 1　立位安静時の腰背筋活動
（A）代表症例の筋活動；後弯症（LDK）患者での筋活動が高い
（B）各群での 1 分間の筋活動量；ボランティアと比較して LDK 患者の上位腰椎での筋活動が有意に高い

でも筋活動が高く，特にアライメント変化の影響を受けやすい上位腰椎レベルでの筋活動が高くなったと思われる．また，LCS 群の立位筋活動が LDK 群およびボランティアと差がないことから腰椎上位での筋活動増加は，腰椎後弯そのものが一因となっていることが示唆される．

筋疲労テストでは，LDK 群の腰椎上位，下位レベルでボランティアと比較して筋疲労の増加を

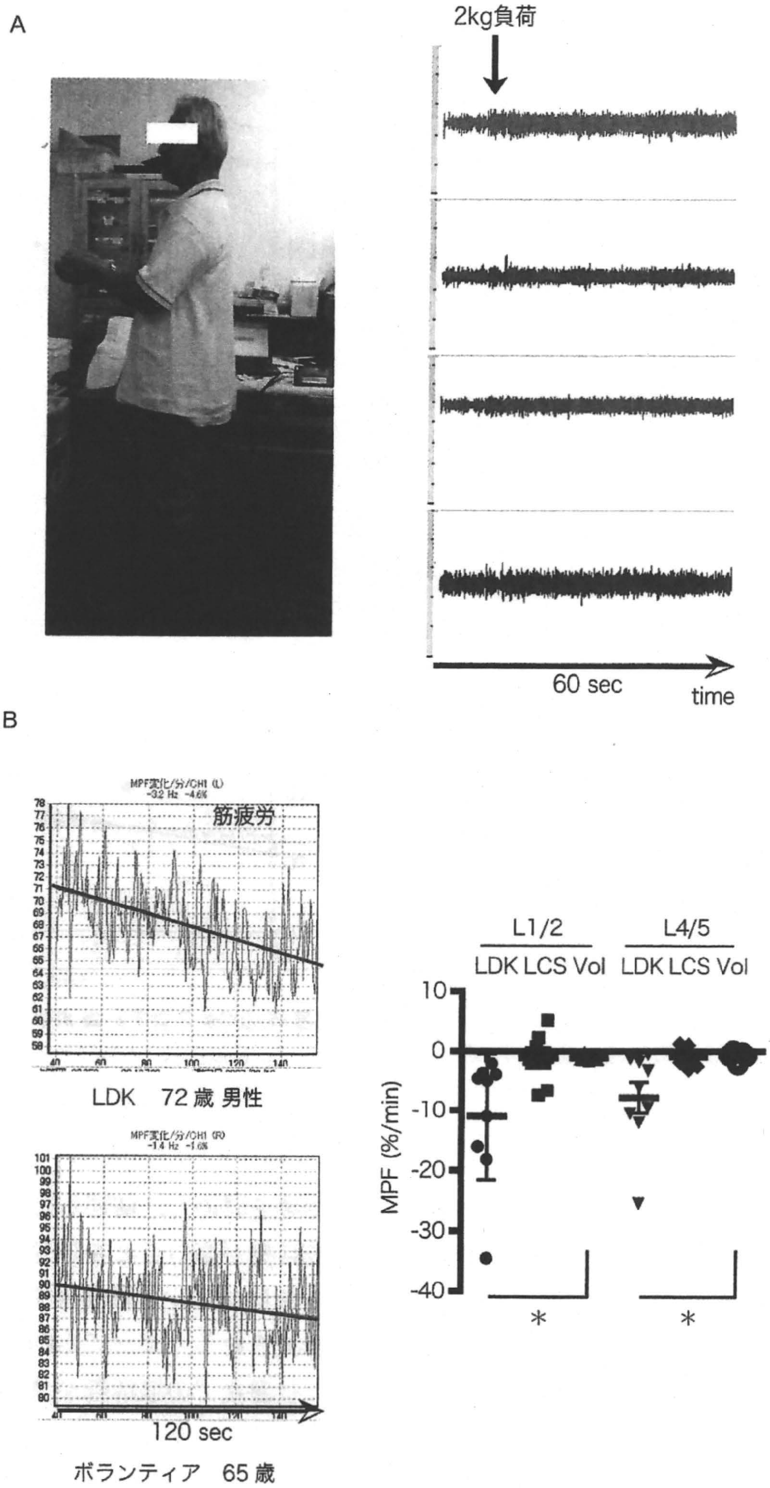

図2 立位筋疲労テスト

（A）体前に2kgの重錘を保持して記録する；重錘負荷時に筋活動が増加する

（B）筋疲労は，平均パワー周波数（MPF）を算出し減少率を指標とする；ボランティアと比較してLDK患者で筋疲労が強い

ていた．このことは，後弯症の発症機序が椎迫や椎間板変性だけでなく腰背筋活動の影響きく受けている一つの証拠となり得る．腰背筋変性の評価にはMRIが有用であり，後弯症患者では筋委縮や脂肪変性が著明との報告もある[4]．今後，本研究においても筋活動とMRIによる筋

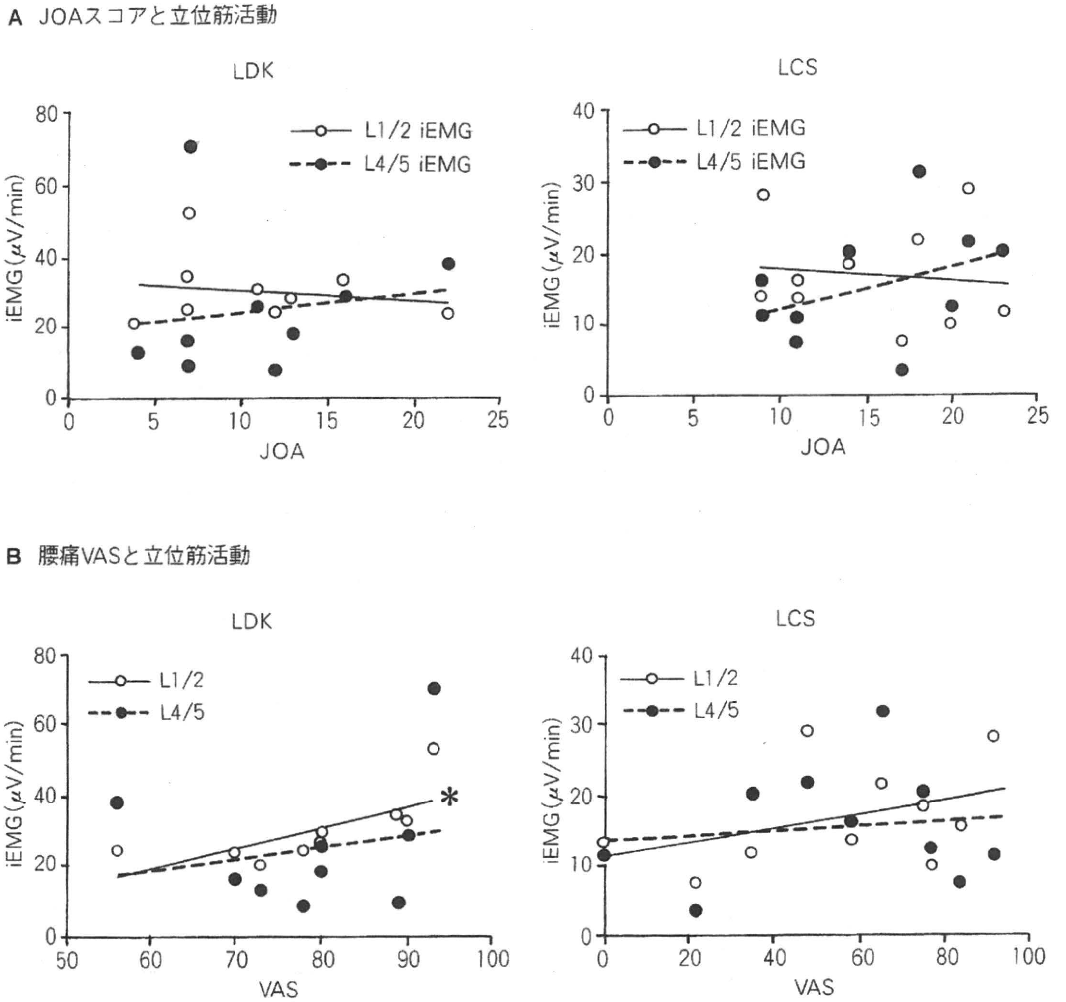

図3　日本整形外科学会腰痛疾患治療成績判定基準（JOAスコア）および腰痛自覚症状（VAS）と腰背筋筋活動との関係

（A）JOAスコアと筋活動；JOAスコアと筋活動に相関は認めなかった
（B）腰痛VASと筋活動；LDK患者の上位腰椎では，VASと筋活動に相関を認めた（*）

変性との関連を検討する必要がある．また，理学療法などによる筋力強化訓練の治療効果判定にも比較的簡便な手技で記録できる表面筋電図は有用と考えられた．

JOAスコアは，自覚症状，他覚所見，日常生活動作，膀胱機能を含んだ指標となっておりLDK群とLCS群両方で筋活動との相関はなかった．腰痛VASを症例ごとに解析するとLCS群では，腰痛が強くてもL1/2あるいはL4/5レベルでの筋活動が低い例もあり相関を示さなかった．この原因の一つに腰痛や下肢痛が長く継続したことによる腰背筋萎縮によって筋活動低下を示した可能性がある．それに対しLDK群では，腰痛が強いほど上位腰椎の筋活動が高くなる傾向があり相関を認めた．前述したように上位腰椎での立位筋活動が高いことを併せて考えると腰痛が軽減し前弯位が少しでも改善すれば筋活動は低下すると推測される．よってLDK患者の治療に際しては，上位腰椎での筋活動が良い指標になり得る．さらに後弯症の病態を理解するために表面筋電図評価以外にもレントゲンによる立位全脊柱アライメント，体幹傾斜角の計測や重心動揺等を含めた評価が必要である．今後は，腰部脊柱管狭窄症や脊椎後弯症手術例に対して筋活動記録を行い，手術による脊柱アライメント変化や症状変化との関係を明らかにする必要がある．

まとめ

今回，簡便な表面筋電図計を用いて脊椎変性疾患を有する高齢者の腰背筋筋活動を記録し定量的に評価することが可能であった．数々の要素とともに脊柱を支える腰背筋の筋活動量および疲労を解析した結果，腰椎後弯症では，ボランティアと比較して立位時に腰椎上位での筋活動が高く易疲労性を示していた．腰部脊柱管狭窄症患者と異なり後弯症患者では腰痛が強いほど腰背筋活動が高くなることがわかった．今後，表面筋電図を用いて高齢者腰痛疾患患者の腰背筋活動を記録・解析を継続することによって従来にない評価方法が確立され，治療指針としても有用となる可能性がある．

文　献

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Cordotomy for patients with thoracic malignant astrocytoma

Clinical article

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Object. The optimal management of malignant astrocytomas remains controversial, and the prognosis of these lesions has been dismal regardless of the administered treatment. In this study the authors investigated the surgical outcomes of cordotomy in patients with thoracic malignant astrocytomas to determine the effectiveness of this procedure.

Methods. Cordotomy was performed in 5 patients with glioblastoma multiforme (GBM) and 2 with anaplastic astrocytoma (AA). A Kaplan-Meier survival analysis was performed, and the associations of the resection level with survival and postoperative complications were retrospectively examined.

Results. Cordotomy was performed in a single stage in 2 patients with GBM and in 2 stages in 3 patients with GBM and 2 patients with AA. In the 2 patients with GBM, cordotomy was performed 2 and 3 weeks after a partial tumor resection. In the 2 patients with AA, the initial treatment consisted of partial tumor resection and subtotal resection combined with radiotherapy, and rostral tumor growth and progressive paralysis necessitated cordotomy 2 and 28 months later. One patient with a secondary GBM underwent cordotomy; the GBM developed 1 year after subtotal resection and radiotherapy for a WHO Grade II astrocytoma. Four patients died 4, 5, 24, and 42 months after the initial operation due to CSF dissemination, and 3 patients (2 with GBM and 1 with AA) remain alive (16, 39, and 71 months). No metastasis to any other organs was noted.

Conclusions. One-stage cordotomy should be indicated for patients with thoracic GBM or AA presenting with complete paraplegia preoperatively. In patients with thoracic GBM, even if paralysis is incomplete, cordotomy should be performed before the tumor disseminates through the CSF. Radical resection should be attempted in patients with AA and incomplete paralysis. If the tumor persists, radiotherapy and chemotherapy are indicated, and cordotomy should be reserved for lesions growing progressively after such second-line treatments.
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Key Words • **malignant astrocytoma** • **thoracic spinal cord** • **cordotomy** • **prognosis**

Spinal cord tumors account for 2–4% of CNS neoplasms in adults, and one-third of these tumors are intramedullary.[2,3,14,15] The majority are gliomas, either astrocytoma or ependymoma, depending on the level of the cord and the age of the patient. Malignant astrocytoma of the spinal cord is extremely rare and one of the most difficult malignant tumors to cure, despite advances in neuroimaging techniques, molecular biology, and novel therapeutic approaches. According to recent reports, the prognosis of this tumor is grave and unlikely to improve, regardless of the operative procedure chosen or the use of radiotherapy and/or chemotherapy, with a mean survival rate of approximately 1 year.[12,13,16] Because rostral progression or dissemination of the tumor is a major cause of death in patients with malignant spinal cord astrocytomas, we have attempted to treat such patients with cordotomy. The purpose of the present study was to determine the efficacy of cordotomy for thoracic malignant astrocytomas.

Abbreviations used in this paper: AA = anaplastic astrocytoma; GBM = glioblastoma multiforme.

Methods

The institutional review board of Keio University approved this study.

The study included 7 patients (6 males and 1 female) between the ages of 13 and 63 years (mean ± SEM, 39 ± 15.9 years), who underwent the initial operation at our hospital between 2003 and 2009. The tumor was diagnosed as GBM in 4 patients and AA in 2. In the remaining patient, the tumor was initially diagnosed as Grade 2 astrocytoma but was later determined to be a secondary GBM. The most cranial levels of the tumors, assessed by MR imaging, were as follows: 1 case each at T-2, T-3, T-5, T-6, and T-10; and 2 cases at T-8. Basically the cordotomy was performed at the T2–3 level to prevent rostral tumor progression without causing any neurological deficits in the upper extremities. In brief, after a T2–3 laminectomy, the dura mater and arachnoid were incised and opened longitudinally. The spinal cord was transected at the T2–3 level, and approximately 1 cm of the caudal part of the spinal cord was removed and subjected to biopsy sampling. If no tumor was found in the resected spinal cord, the dura mater was transected, both cut ends were tightly closed, and the dead space was filled with fibrin glue to prevent CSF leakage. If any tumor was detected in the resected spinal cord, additional cordectomy was performed until biopsy sampling revealed a negative result. We analyzed the clinical courses of the patients and investigated the relationships between the survival of individual patients and the spinal cord segment in which the tumor developed, the spinal cord segment in which the cordotomy was performed, and the time from the initial operation to the cordotomy.

Results

Initial and Preoperative Neurological Symptoms

The initial symptom was numbness of the legs in 4 patients and back pain in 3. The paralysis advanced rapidly in all patients, except for the patient with a Grade 2 astrocytoma (Case 7). Upon admission, the Frankel grade was A in 2 patients (Cases 1 and 2), C in 4 (Cases 3–6), and D in 1 (Case 7). All patients had bladder dysfunction.

Surgical Procedures

In all cases, biopsy sampling was done before any treatment was initiated. Two patients with GBM who had complete preoperative paraplegia (Cases 1 and 2) underwent cordotomy as a primary procedure. The other 5 patients had incomplete preoperative paralysis; partial resection was performed in the 2 patients with GBM (Cases 3 and 4) and subtotal resection was conducted in the 2 patients with AA (Cases 5 and 6) and in the patient with a Grade 2 astrocytoma (Case 7). Although the 2 patients with GBM (Cases 3 and 4) who were treated with partial resection were not completely paraplegic, cordotomy was performed 2 or 3 weeks after the initial operation under informed consent to prevent rostral tumor progression and CSF dissemination. In Case 5, radiotherapy (50 Gy) was administered after the partial resection, but rostral tumor progression necessitated cordotomy 2 months after surgery. In Case 6, subtotal resection and radiotherapy (50 Gy) resulted in a favorable course, but the paralysis aggravated again 28 months after the initial operation due to rostral tumor progression. This patient then underwent cordotomy. In Case 7, biopsy sampling during the initial operation revealed a Grade 2 astrocytoma, and subtotal resection was performed, followed by radiotherapy (50 Gy). Eleven months after the initial operation, the tumor showed rapid rostral progression, and chemotherapy with temozolomide was administered. However, the tumor continued to grow rostrally, and a second biopsy procedure indicated the diagnosis of secondary GBM. This patient underwent cordotomy 12 months after the initial operation.

To avoid dysfunction of the arms, cordotomy was first undertaken at the T2–3 level in all of the patients. In 3 cases in which intraoperative pathological examination had revealed a tumor cell–positive stump, the spinal cord was transected at more cranial levels: T1–2 (Cases 1 and 2) or C7–T1 (Case 6). Before cordotomy, none of the

TABLE 1: Clinical characteristics of 7 patients with malignant astrocytoma of the thoracic spinal cord

Case No	Age (yrs), Sex	Primary Surgery	WHO Tumor Grade	Preop Frankel Grade	Original Rostral Level of Tumor	Interval Btwn Primary Surgery & Cordotomy	Level of Cordotomy	Prognosis	Length of Survival (mos)	Complication
1	13, M	cordectomy	IV	A	T-2	0	T1–2	dead	4	none
2	63, M	cordectomy	IV	A	T-3	0	T1–2	dead	5	none
3	42, M	partial resection	IV	C	T-5	3 wks	T2–3	alive	16	allodynia
4	49, M	partial resection	IV	C	T-8	2 wks	T2–3	alive	39	none
5	49, M	partial resection	III	C	T-8	2 mos	T2–3	alive	71	none
6	30, M	subtotal resection	III	C	T-10	28 mos	C7–T1	dead	42	limbic encephalitis
7	40, F	subtotal resection	II→IV	D	T-6	12 mos	T2–3	dead	24	limbic encephalitis

patients had tumor invasion to the brain or cervical spinal cord on MR imaging. Clinical data for the 7 cases are summarized in Table 1 and Fig. 1.

Disease Prognosis

Of the 7 patients, 4 (Cases 1, 2, 6, and 7) died 4, 5, 42, and 24 months, respectively, after the initial operation due to CSF dissemination resulting in respiratory failure (Fig. 2). Three patients (Cases 3–5) were alive at the time of their last follow-up evaluation, with survival periods of 16, 39, and 71 months from the initial operation, respectively. Residual tumor was found in the distal spinal cord of all 3 survivors, but there was no tumor invasion above the level of cordotomy. No tumor metastasis to other organs was noted in any of the patients.

Patient Complications

All patients experienced temporary belt-lined pain at the level of the cordotomy. The patient in Case 3 experienced pain in both lower extremities 2 months after cordotomy, which was alleviated shortly after the administration of gabapentin and clonazepam but again worsened, and thus the patient is now taking morphine. The patients in Cases 6 and 7 suffered dysosmia and impaired short-term memory due to the development of limbic encephalitis. None of the patients experienced any other complications such as meningitis, CSF leakage, or hydrocephalus.

Illustrative Cases

Case 3

This 42-year-old man's initial symptom was numbness of the right leg. Six months later, gait disturbance (due to muscular weakness in his legs) and a vesicorectal dysfunction developed. The preoperative Frankel grade was C. Preoperative MR imaging revealed a tumor at the T5–6 level (Fig. 3a and b). The results of intraoperative biopsy sampling revealed that the tumor was a GBM. Partial resection was performed because the border between the tumor and the spinal cord was obscure. After the initial operation, the patient's paralysis did not progress; therefore, cordotomy at the T2–3 level was performed (with informed consent) 3 weeks after the initial operation. At present, 16 months after the cordotomy, there is residual tumor in the caudal spinal cord below the site of transection but without signs of rostral tumor invasion or metastasis to any other organs (Fig. 3c and d).

Case 6

This 30-year-old man's initial symptom was back pain. Three months later, he became unable to walk because of pain and weakness in his legs. The preoperative Frankel grade was C. Preoperative MR imaging revealed a tumor at the T10–12 levels, visualized as high signal intensity areas on T2-weighted images. The tumor was heterogeneously enhanced by Gd (Fig. 4a and b). Biopsy results indicated the diagnosis of AA. Although the tumor was not well demarcated from the spinal cord, subtotal re-

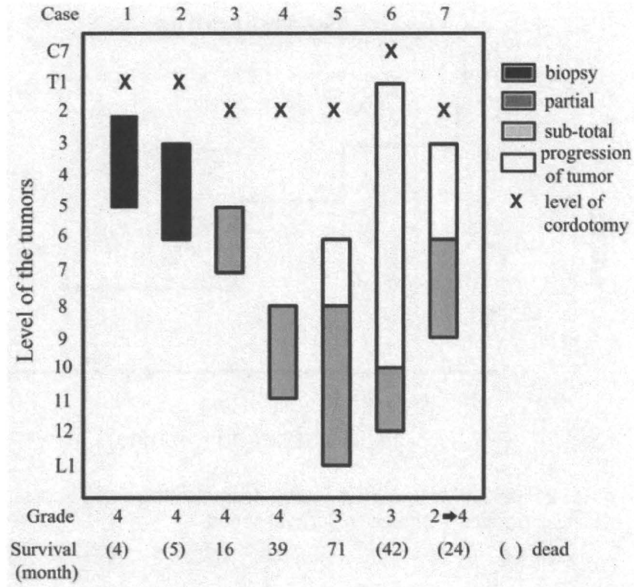


Fig. 1. Graph showing the distribution of tumors and surgical procedures.

section with a Cavitron ultrasonic surgical aspirator was performed (Fig. 4c and d). Postoperatively, the patient's paralysis temporarily worsened, but his leg pain was alleviated. After radiotherapy, he was discharged from the hospital, walking with a cane. His paralysis worsened again 2 years after the surgery. Because MR imaging revealed tumor recurrence, chemotherapy with temozolomide was started but produced no response, and thus a cordotomy was indicated. The spinal cord was initially transected at the T2–3 level, but because tumor cells were present at the stump, additional resection at a higher level, C7–T1 (Fig. 4e and f), was necessary. Cerebrospinal fluid dissemination occurred 1 year after the cordotomy, and the patient died of central respiratory failure 3 years and 6 months after the initial operation (Fig. 4g and h).

Discussion

Recent reports have shown that benign intramedullary astrocytoma of the spinal cord can be well managed by radical resection, which is associated with an improvement in neurological function and possibly an increase in survival time.[1,2,10–13] However, the prognosis in patients with malignant astrocytoma (WHO Grade III or IV) has been poor regardless of treatment, and the majority of patients die within 2 years from either tumor progression or dissemination.[13,16] Therefore, cordectomy has been advocated for the treatment of thoracic malignant astrocytoma, even though patients completely lose neurological function at and below the level of the cordectomy.

In 1949 MacCarty and Kiefer[6] reported on a case of malignant astrocytoma at a high thoracic level with complete paralysis of the legs presurgically. In an effort to eradicate the tumor, which had been identified through biopsy sampling 6.5 months earlier, the patient underwent a thoracic, lumbar, and sacral spinal cordectomy with a

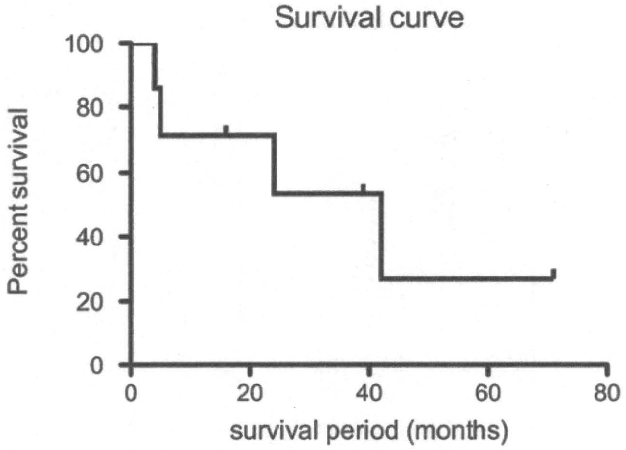


FIG. 2. Kaplan-Meier survival curve demonstrating the percentage of surviving patients for a given survival period.

3-stage resection 2.3 years after the onset of symptoms. The procedure resulted in the removal of the entire spinal cord except the cervical and first thoracic segment; however, the patient died 7 months later (Table 2).[5–7] This case is similar to our Cases 1 and 2 in terms of 1) the presence of complete preoperative paralysis due to GBM, 2) the proximity of the tumor to the level of cordectomy/cordotomy, and 3) the occurrence of CSF dissemination approximately half a year after cordectomy/cordotomy.

In view of the results of previous surgeries,[13,16] it seems rational to indicate cordotomy for patients in whom complete preoperative paralysis is present and biopsy sampling confirms the diagnosis of GBM. In our Cases 1 and 2, however, CSF dissemination occurred soon after cordotomy, even though there was no sign of CSF dissemination on preoperative MR imaging and the cytodiagnosis of the CSF was negative. One possible explanation for this consequence is that tumor cells disseminated into the CSF during surgery, because the level of cordotomy was close to the tumor margin. In view of these results, we are hesitant to advocate cordotomy for patients with tumors located in the upper thoracic spinal cord (above the T-3 level).

Kyoshima et al.[4] reported that despite multiple tumor resections and additional multiple cordectomies performed for tumor recurrence in a paraplegic patient with a malignant astrocytoma (AA) of the medullary conus (T8–L1), the patient ultimately died of tumor recurrence and dissemination 5 years after the primary surgery. These authors performed cordectomy 3 times at the level 1–3 segments cranial to the level of the tumor. Even when the stump was free of tumor cells following surgical removal, CSF dissemination occurred postoperatively because the optimal level of cordectomy relative to the most rostral tumor margin was unknown. However, given that Kyoshima et al. found that tumor dissemination could not be prevented when the margin was 3 segments or less, we have made it a rule to perform cordotomy at the T2–3 level (the level unlikely to cause dysfunction of the upper extremities), regardless of the level at which the tumor has developed, with the goal of minimizing CSF dissemination (Table 2).

Using this basic treatment strategy, 3 of our patients have survived 16, 39, and 71 months after cordotomy, including 1 patient with a GBM at the T-5 level and 2 patients with tumors (GBM and AA) at the T-8 level. To date, these 3 patients have shown no signs of CSF dissemination on MR imaging. The survival periods for the patients in these cases are favorable compared with those in previously reported cases.[9,13,16] However, Marchan et al.[8] reported that a patient with a GBM of the spinal cord (T-11 level), who was treated with surgical removal of the mass and cordectomy (T8–L1 level), died due to CSF dissemination 6 years after the cordectomy (Table 2). Cerebrospinal fluid dissemination may still develop in our 3 surviving patients; thus, careful monitoring with MR imaging is essential.

One difference between previously reported cases and ours is that our patients underwent cordotomy instead of cordectomy. Cordectomy, which involves resection of the tumor itself, requires extensive laminectomy and causes high operative stress for patients if the procedure is performed with an adequate margin. In past reports, all patients in whom cordectomy was performed at the level 3 segments cranial to the tumor margin demonstrated postoperative CSF dissemination.[4–8] Therefore, with the

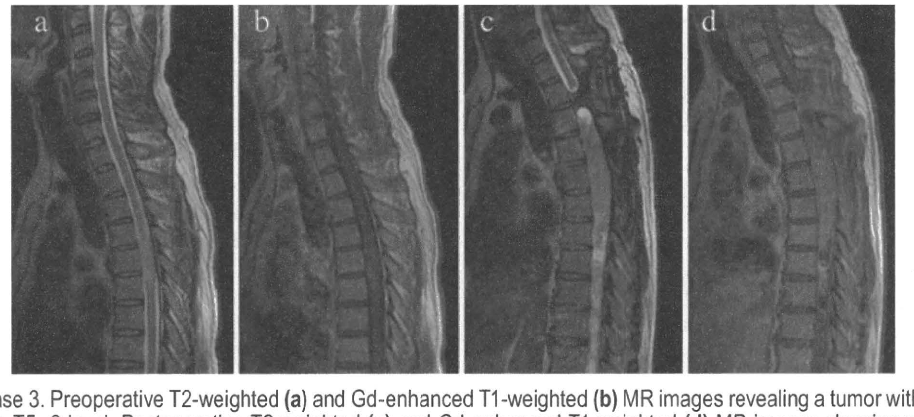
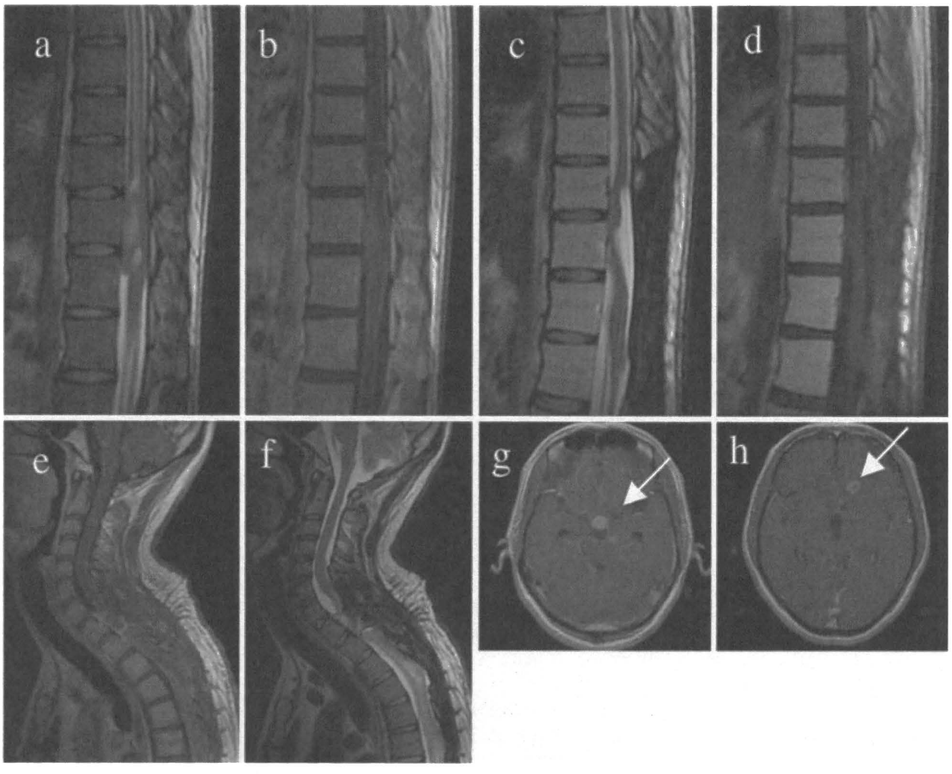


FIG. 3. Case 3. Preoperative T2-weighted **(a)** and Gd-enhanced T1-weighted **(b)** MR images revealing a tumor with an unclear margin at the T5–6 level. Postoperative T2-weighted **(c)** and Gd-enhanced T1-weighted **(d)** MR images showing rostral tumor progression blocked at the level of cordotomy.



Fɪɢ. 4. Case 6. Preoperative T2-weighted **(a)** and Gd-enhanced T1-weighted **(b)** MR images showing T2 high signal and heterogeneously Gd-enhanced tumor at the T10–12 levels. Sagittal T2-weighted **(c)** and Gd-enhanced T1-weighted **(d)** MR images obtained after primary surgery, demonstrating no residual tumor. Sagittal Gd-enhanced T1-weighted **(e)** and T2-weighted **(f)** MR images obtained after cordotomy at C7–T1, showing no tumor cells at the stump of the cordotomy. Axial Gd-enhanced T1-weighted MR images **(g and h)** obtained 1 year after cordotomy, revealing CSF dissemination *(arrows)*.

intent of minimizing the invasiveness of the procedure as well as the potential for CSF dissemination, we have decided to perform cordotomy at the upper thoracic spinal cord instead of radical cordectomy.

Even when cordotomy is performed in the upper thoracic segments, tumor cells remain in the spinal cord caudal to the level of the cordotomy. In the past, the metastasis of highly malignant astrocytoma cells to organs or systems other than the CNS was considered to be quite rare. However, Santi et al.[16] reported metastasis to the liver and spleen in 2 of 36 patients with highly malignant astrocytomas (1 patient each with GBM and AA). Thus, even when cranial tumor progression and CSF dissemination is prevented after cordotomy, we cannot rule out the possibility of metastasis to other organs during the follow-up period. Although the mechanism of the metastasis of highly malignant astrocytomas to organs outside the CNS remains to be clarified, the most likely mechanism is blood-borne metastasis following tumor growth and the collapse of the blood–spinal cord barrier, considering that the reported metastases occurred in the liver and spleen. Thus, given the risk for metastasis to other organs, although low, we probably need to consider second-stage or radiational cordectomy when dealing with patients in whom CSF dissemination does not take place after cordotomy and the residual tumor shows rapid growth.

Conclusions

On the basis of these findings, we propose the following strategy for the treatment of thoracic malignant astrocytoma. In patients in whom complete preoperative paralysis is present and biopsy confirms the diagnosis of

TABLE 2: Summary of studies on cordectomy for patients with malignant astrocytoma of the thoracic spinal cord

Authors & Year	Age (yrs), Sex	Primary Surgery	WHO Tumor Grade	Preop Frankel Grade	Original Rostral Level of Tumor	Interval Btwn Primary Surgery & Cordectomy	Prognosis	Length of Survival (mos)
MacCarty, 1954	27, M	biopsy	IV	A	T-3	6.5 mos	dead	7
Kyoshima et al., 2002	48, M	subtotal resection	III	A	T-8	4 yrs	dead	60
Marchan et al., 2007	50, M	partial resection	IV	A	T-8	3 mos	dead	72

GBM or AA, primary cordotomy should be considered to minimize CSF dissemination. Even in patients with incomplete preoperative paralysis, it is advisable to perform cordotomy as soon as possible after obtaining informed consent if the diagnosis of GBM is histopathologically confirmed. Cordotomy is not indicated in cases in which preoperative brain MR imaging and CSF tests indicate CSF dissemination. In patients with AA and incomplete paralysis, radical resection should be attempted first, as recommended in past reports.[13] If the tumor persists after surgery, radiotherapy and/or chemotherapy should be administered, and tumor recurrence or regrowth must be carefully checked on MR imaging. Cordotomy should be considered in cases with rostral tumor progression after such second-line treatments. To determine the optimal timing of cordotomy in patients with AA and incomplete paralysis, further studies are necessary.

Disclosure

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

Author contributions to the study and manuscript preparation include the following. Conception and design: Nakamura. Acquisition of data: Nakamura, O Tsuji, Fujiyoshi, Watanabe, T Tsuji, Ishii, Matsumoto, Chiba. Analysis and interpretation of data: Nakamura, Fujiyoshi, Chiba. Drafting the article: Nakamura. Critically revising the article: Nakamura, Toyama, Chiba. Reviewed final version of the manuscript and approved it for submission: all authors. Study supervision: Toyama, Chiba.

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A Novel Pedicle Channel Classification Describing Osseous Anatomy

How Many Thoracic Scoliotic Pedicles Have Cancellous Channels?

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Study Design. Prospective clinical series.

Objective. To determine how many thoracic scoliotic pedicles have cancellous *versus* cortical *versus* absent channels.

Summary of Background Data. Although morphologic evaluations of thoracic pedicles have been well reported, the results do not practically reflect clinical findings during actual pedicle screw placement. We propose a novel pedicle channel classification describing the osseous anatomy encountered during pedicle probe insertion.

Methods. We noted 4 pedicle types in 53 consecutive scoliosis patients. Type A: pedicle probe smoothly inserted without difficulty; the morphology is described as a "Large Cancellous Channel." Type B: pedicle probe inserted snugly with increased force; described as a "Small Cancellous Channel." Type C: pedicle probe cannot be manually pushed but must be tapped with a mallet down the pedicle into the body; described as a "Cortical Channel." Type D: pedicle probe cannot locate a channel thus necessitating a "juxtapedicular" screw position; described as a "Slit/Absent Channel." The average age at time of surgery was 23.4 ± 16.7 years. Diagnoses included idiopathic scoliosis (n = 38) and syndromic scoliosis (n = 15). The average main thoracic Cobb angle was 73° ± 26°. Evaluation of pedicle morphology of the 4 types was also performed in 21 consecutive cases of adolescent idiopathic scoliosis using preoperative computed tomography images.

Results. A total of 1021 pedicles with screws placed were evaluated. The average percent per type was as follows: 61.0% type A; 29.2% type B, 6.8% type C, and 3.0% type D. On the convexity, 98.2% of pedicles were type A or B *versus* 81.5% on the concavity ($P < 0.05$). There were significant differences between adolescent *versus* adult idiopathic scoliosis ($P = 0.007$), and syndromic scoliosis *versus* adult idiopathic scoliosis ($P = 0.017$) regarding pedicle morphologic proportions. There was a significant tendency toward a decrease in the proportion of type A pedicles, an increase in the proportion of type B pedicles as the Cobb angle increased ($P < 0.0001$). Evaluation based on 312 thoracic pedicles in 21 consecutive adolescent idiopathic scoliosis patients using preoperative computed tomography axial images confirmed assumptions of the 4 pedicle types.

Conclusion. We propose a classification for pedicle channels describing the osseous anatomy encountered during pedicle probe insertion. Based on the classification, surprisingly, we found during surgery that 90% of thoracic pedicles had a cancellous channel, whereas 7% had a cortical channel and only 3% had an absent channel.

Key words: pedicle morphology, pedicle screws, adolescent idiopathic scoliosis, adult idiopathic scoliosis. **Spine 2010;35:1836–1842**

Because thoracic pedicle screw constructs have been reported to have better corrective ability than hook and wire constructs in the treatment of scoliosis,[1–4] corrective surgery using thoracic pedicle screw constructs has become standard at many centers.[5–7] However, concerns regarding the risks of major neurologic and vascular complications still remain.[8–10] To reduce such potential catastrophic complications, morphologic evaluation of thoracic pedicles in patients with scoliosis using computed tomography (CT)[11,12] and magnetic resonance imaging[13] have recently been reported. In these reports, adolescent idiopathic scoliosis (AIS) has been described to have asymmetric morphology of pedicles with significantly smaller pedicles on the concave side of the curve than on the convex side. However, these reports did not practically reflect clinical findings during pedicle screw placement, especially regarding feasibility of navigating down the thoracic pedicle into the vertebral body before screw placement. For safe and accurate placement of pedicle screws, the surgeon needs to know whether the pedicle has a cancellous channel *versus* cortical channel *versus* no channel while navigating a pedicle probe into the vertebral body. Therefore, information regarding how many cancellous pedicles exists and where the cancellous pedicles are located in the thoracic spine becomes especially important.

In this study, we propose a novel pedicle channel classification describing the osseous anatomy encountered during pedicle probe insertion, which consists of 4 pedicle types. Based on the classification, we prospectively investigated the proportion and distribution of these 4 types in patients with scoliosis and confirmed their morphology by CT imaging.

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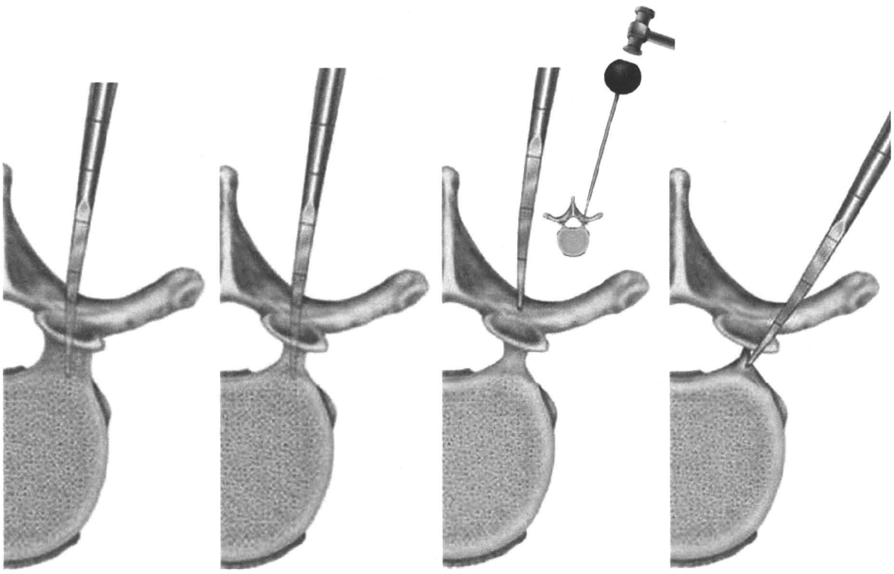

Figure 1. Novel pedicle channel classification.

■ Materials and Methods

Novel Pedicle Channel Classification

We noted 4 pedicle types, designated as A, B, C, and D (Figure 1). Type A, a "Large Cancellous Channel" is assigned when the pedicle probe is smoothly inserted without difficulty. Type B, a "Small Cancellous Channel" is assigned when the pedicle probe is inserted snugly with increased force. Type C, a "Cortical Channel" is assigned when the pedicle probe cannot be manually pushed but must be tapped with a mallet into the pedicle channel into the body. Type D, a "Slit/Absent Pedicle Channel" is assigned when the pedicle probe cannot locate a pedicle channel thus necessitating a juxtapedicular screw position.

Proportion and Distribution of Pedicle Types

Between November 2005 and December 2006, we prospectively recorded the 4 pedicle types in a consecutive series of scoliosis patients treated at one institution. Data collection was performed after Institutional Review Board Human Studies Committee approval. Patients who had previous surgery were excluded. All surgeries were performed by one surgeon and assignment of pedicle types based on the aforementioned descriptions during the surgeries were also performed by one surgeon and visually confirmed by another surgeon viewing the procedure. The "free hand" technique of pedicle screw placement was performed as reported by Kim *et al.*[5] If the pedicle screw was in malposition, the pedicle type was excluded from the data except for type D pedicles wherein the screws were intentionally placed lateral to the pedicle. Pedicle screw malposition was determined based on the criteria validated by Kim *et al*[5] using intraoperative radiographs.

Fifty-three consecutive patients (10 males and 43 females) with scoliosis were included in this study (Table 1). The average age at time of surgery was 23.4 ± 16.7 years (range, 10–65 years). Diagnoses included 38 idiopathic scoliosis patients (adolescent: 28 cases, adult: 10 cases), and 15 syndromic scoliosis patients (cerebral palsy: 5 cases, Marfan syndrome: 3 cases, spinal muscle atrophy: 1 case, Down syndrome: 1 case, Greig's syndrome: 1 case, congenital muscular dystrophy: 1 case). In all patients, the apex of the major curve was located in the thoracic spine. The average Cobb angle of the major curve was 73° ± 26° (range, 45°–127°).

Proportion of the 4 pedicle types, proportion of pedicle types dependent on the diagnosis (AIS *vs.* adult idiopathic scoliosis *vs.* syndromic scoliosis), proportion of pedicle types dependent on laterality (concave *vs.* convex), distribution of type C and D pedicles in the thoracic spine, and proportion of pedicle types dependent on the magnitude of the Cobb angle of the main curve were evaluated. Preoperative Cobb angles were measured on the standing long-cassette AP radiograph.

Morphologic Evaluation Using CT Imaging

Evaluation of pedicle morphology of the 4 pedicle types was also performed using preoperative CT images on a separate investigation. Twenty-one consecutive cases of AIS were included for this evaluation. The surgeries were performed between December 2006 and March 2008 by 2 surgeons, who were different from the senior surgeon, at different institutions. The average age at time of surgery was 14.0 ± 1.8 years (range, 11–16 years) and the average Cobb angle was 65° ± 9° (range,

Table 1. Demographics of Patients

	Adolescent Idiopathic Scoliosis	Adult Idiopathic Scoliosis	Syndromic Scoliosis	Total
No. patients	28	10	15	53
Male	3	0	7	10
Female	25	10	8	43
Average age (yr)	16.8 ± 3.2*	55.1 ± 12.4	14.6 ± 3.1*	23.4 ± 16.7
Average Cobb angle (°)	69.6 ± 19.9	65.9 ± 14.5	80.9 ± 21.4	72.3 ± 25.5

*Significant difference by Mann-Whitney *U* test *versus* adult idiopathic scoliosis.

50°–90°). The assignment of pedicle types was performed by the surgeons. Morphologic evaluation using an axial image of fine cut (width, 1.25 mm) from a preoperative CT scan was performed. All thoracic levels were scanned with the gantry set parallel to the pedicles. Pedicle width at the isthmus, width of the cancellous channel, percentage of cancellous width compared with the pedicle width, and the proportion of cortical channel pedicles (*i.e.*, pedicle, which has no cancellous bone at the isthmus) were evaluated in the 4 pedicle types. In the measurements of the pedicle width, a minimum distance between the outer cortices of the pedicle at the isthmus was measured. In the measurement of cancellous bone width, a minimum cancellous width at the isthmus was measured. In the evaluation of the proportion of cortical channel pedicles, these were defined as pedicles that had no visual cancellous bone at the isthmus on axial CT images. All measurements were performed using NIH image software by an independent observer in a blind manner.

Statistical Analyses

χ^2 test was used for the occurrence comparison of the 4 pedicle types. Mann-Whitney *U* test and χ^2 test were used in the evaluation of pedicle morphology using CT images. Statistical significance was defined as $P < 0.05$. Statistical analysis was performed using SPSS, version 10.0 (Chicago, IL).

■ Results

Proportion of Pedicle Types

A total of 1021 pedicles in which pedicle screws were placed from T2–T12 were evaluated. Overall, there were 623 type A pedicles (61.0%), 298 type B pedicles (29.2%), 69 type C pedicles (6.8%), and 31 type D pedicles (3.0%) recorded (Table 2, Figure 2). The results indicated that 90.2% (types A and B) of all pedicles had a cancellous channel that could be readily navigated with a standard pedicle probe.

Proportion of Pedicle Types to Diagnoses

In AIS patients, 254 type A pedicles (54%), 157 type B pedicles (33%), 39 type C pedicles (8%), and 24 type D pedicles (5%) were found (Table 2, Figure 2). In adult idiopathic scoliosis, 160 type A pedicles (78%), 45 type B pedicles (22%), 1 type C pedicle (1%), and no type D pedicles were noted. In syndromic scoliosis, 209 type A pedicles (61%), 96 type B pedicles (28%), 29 type C pedicles (9%), and 7 type D pedicles (2%) were recorded. There were statistically significant differences in AIS *versus* adult idiopathic scoliosis ($P = 0.007$), and syndromic scoliosis *versus* adult idiopathic scoliosis ($P = 0.017$) regarding the proportion of all 4 pedicle types. However, there were no significant differences between AIS and syndromic scoliosis.

Proportion of Pedicle Types and Laterality

On the convex side, 325 pedicles (75.6%) were type A, 97 pedicles (22.6%) were type B, 6 pedicles (1.4%) were type C, and 2 pedicles (0.5%) were type D. Therefore, 98.2% of pedicles on the convex side had a cancellous channel (Table 3, Figure 3). Conversely, on the concave side, 200 pedicles (46.3%) were type A, 152 pedicles (35.2%) were type B, 57 pedicles (13.2%) were type C, and 23 pedicles (5.3%) were type D (Figure 3). There

Table 2. Distribution of Pedicle Types and Diagnoses

	Syndromic*								AIS†								Adult IS*†								All Diagnoses	
	Convex	%	Concave	%	Neutral	%	Total	%	Convex	%	Concave	%	Neutral	%	Total	%	Convex	%	Concave	%	Neutral	%	Total	%	Total	%
A	115	77.2	67	44.4	27	65.9	209	61.3	139	71.3	72	36.9	43	51.2	254	53.6	71	82.6	61	70.9	28	82.4	160	77.7	623	61.0
B	31	20.8	54	35.8	11	26.8	96	28.2	51	26.2	74	37.9	32	38.1	157	33.1	15	17.4	24	27.9	6	17.6	45	21.8	298	29.2
C	3	2.0	24	15.9	2	4.9	29	8.5	3	1.5	32	16.4	4	4.8	39	8.2	0	0.0	1	1.2	0	0.0	1	0.5	69	6.8
D	0	0.0	6	4.0	1	2.4	7	2.0	2	1.0	17	8.7	5	6.0	24	5.1	0	0.0	0	0.0	0	0.0	0	0.0	31	3.0
	149		151		41		341		195		195		84		474		86		86		34		206		1021	

*Significant difference regarding total pedicle types by χ^2 test ($P = 0.017$).
†Significant difference regarding total pedicle types by χ^2 test ($P = 0.007$).
AIS indicates adolescent idiopathic scoliosis; IS, idiopathic scoliosis.

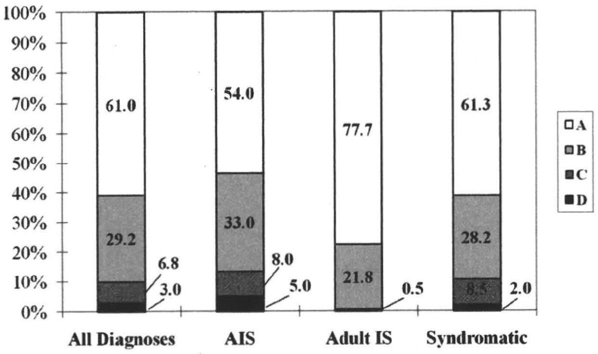

Figure 2. Diagnoses and pedicle types.

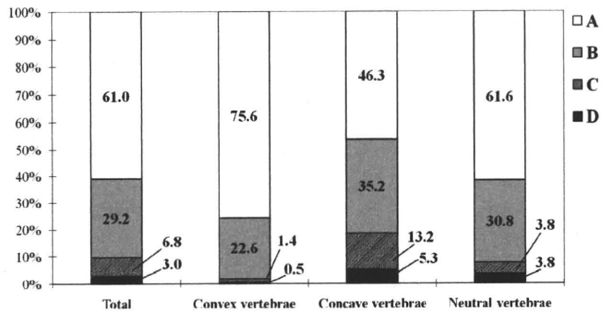

Figure 3. Laterality and pedicle types.

were statistically significant differences between the convex side *versus* the concave side regarding the proportion of types A, C, and D pedicles ($P < 0.0001$).

Distribution of Types C and D Pedicles in the Thoracic Spine

The distribution of type C pedicles had 2 peaks in the thoracic spine. One was located in the proximal thoracic curve and the other in the midthoracic spine, both on the concave side (Figure 4). In addition, the majority of type D pedicles were located on the concave side of the proximal thoracic curve (Figure 5).

Proportion of Pedicle Types to Cobb Angle Magnitude

The pedicle types were divided into 3 groups determined by the Cobb magnitude: 40° to 59°, 60° to 79°, and 80° or larger (Figure 6). There was a significant tendency toward a decrease in the proportion of type A pedicles as the Cobb angle increased ($P < 0.0001$), whereas the proportion of type B pedicles increased as the Cobb angle increased ($P < 0.0001$). The proportion of type C pedicles was significantly higher with Cobb angles >80° *versus* Cobb angles of 60° to 79° ($P = 0.031$). Regarding the proportion of type D pedicles, there was no significant difference among the groups of different Cobb angles ($P = 0.576$).

Morphologic Evaluation of Pedicle Types Using Preoperative CT Scanning

Three hundred twelve thoracic pedicles in 21 consecutive AIS patients were evaluated using preoperative CT axial images. The proportion of pedicle types were 186 type A pedicles (59.6%), 75 type B (24.0%), 30 type C (9.6%), and 21 type D (6.7%). Regarding the proportion of pedicle types, there were no significant differences assigned during the prospective evaluation *versus* those assigned following preoperative CT scan evaluation ($P > 0.05$ for all comparisons).

As measured on the preoperative CT scan, average outer pedicle widths at the isthmus were 5.8 ± 1.7 mm in type A pedicles, 5.0 ± 1.7 mm in type B, 3.7 ± 1.3 mm in type C, and 3.6 ± 1.3 mm in type D (Table 4, Figure 7). There were statistically significant differences between these pedicle types except between types C and D (A *vs.* B; $P = 0.0013$, A and C; $P < 0.0001$, A *vs.* D; $P < 0.0001$, B *vs.* C; $P = 0.0019$, B *vs.* D; $P = 0.0009$, C *vs.* D; $P = 0.8584$).

Regarding the width of cancellous bone at the isthmus, the average widths were 3.4 ± 1.7 mm in type A pedicles, 2.6 ± 1.6 mm in type B pedicles, 1.5 ± 1.3 mm in type C pedicles, and 1.6 ± 1.1 mm in type D pedicles (Table 4, Figure 7). There were significant differences between these pedicle types except between types C and D (A *vs.* B; $P = 0.0016$, A and C; $P < 0.0001$, A and D; $P < 0.0001$, type B *vs.* C; $P = 0.0018$, B *vs.* D; $P = 0.0051$, C *vs.* D; $P = 0.7932$).

The proportions of these cancellous widths compared with pedicle widths at the isthmus were 56% ±16% in type A pedicles, 49% ± 18% in type B, 34% ± 27% in type C, and 38% ± 26% in type D (Table 4, Figure 9). There were statistically significant differences between these pedicle types except between types C and D (A *vs.* B; $P = 0.002$, A and C; $P < 0.0001$, A and D; $P < 0.0001$, B *vs.* C; $P = 0.0038$, B *vs.* D; $P = 0.0294$, C *vs.* D; $P = 0.6108$).

The proportion of pedicles that had no cancellous bone at the isthmus (*i.e.*, cortical channel pedicle) were 1.1% in type A pedicles, 2.7% in type B, 38.5% in type C, and 61.9% in type D (Table 4, Figure 9). There were statistically significant differences between pedicle types

Table 3. Distribution of Pedicle Types (Concave, Convex, Neutral)

	Convex Vertebrae	%	Concave Vertebrae	%	Neutral Vertebrae	%	Total	%
A	325	75.6*	200	46.3*	98	61.6	623	61.0
B	97	22.6	152	35.2	49	30.8	298	29.2
C	6	1.4*	57	13.2*	6	3.8	69	6.8
D	2	0.5*	23	5.3*	6	3.8	31	3.0
Total	430		432		159		1021	

*Significant difference by χ^2 test between convex *versus* concave.