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Neural Complications in the Surgical Treatment of Adolescent Idiopathic Scoliosis

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Study Design. Multicenter, prospective, consecutive clinical series.

Objective. To report on neural complications in a prospective cohort study of 1301 children undergoing spinal fusion and instrumentation for adolescent idiopathic scoliosis (AIS).

Summary of Background Data. The incidence of neural complications for spinal deformity surgery has been reported to be 0.26% to 17%. However, most studies have relied on retrospective voluntary reporting of nonconsecutive cases.

Methods. A review of 1301 consecutive surgical cases was conducted using the Prospective Pediatric Scoliosis Study database, which is maintained by the Spinal Deformity Study Group.

Results. There were 9 neural complications. There were 3 thecal penetrations, none of which required repair, and none of which demonstrated intraoperative neural monitoring changes or postoperative clinical sequelae. There were 2 nerve root injuries. In 1 nerve root injury, a positional compression femoral neurapraxia resolved over 6 months. The other was an L4 neurapraxia despite lowest instrumented vertebra L1, and resolved spontaneously by 3 months' follow-up. There were 4 spinal cord injuries. One required removal of implants and fusion *in* situ, 1 required relaxation of correction and *in situ* fusion with instrumentation, while the other 2 were observed after fusion and instrumentation with reduction. All resolved spontaneously within 3 months after operation.

Conclusion. The neural complication rate was 0.69%. Two thecal penetrations were due to medial placement of pedicle screws, and 1 was due to dissection during spine exposure. If these are eliminated, as they imply intraspinal entry but not direct neural injury, together with 1 positional neurapraxia, which is remote from the surgical field, our complication rate is 0.38%. This is consistent with other studies in the North American Literature, including multiple reports from the Scoliosis Research Society. Common themes are significant curve correction producing neural stretch and the use of sublaminar wires. None of the neural injuries was permanent. These results reaffirm that surgical treatment of adolescent idiopathic scoliosis has a low but real neural complication rate.

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Neural complications are the greatest concern for parents and children undergoing spinal fusion with instrumentation for adolescent idiopathic scoliosis.[1] Factors associated with neural complications of operation for adolescent idiopathic scoliosis include type of procedure,[2,3] curve magnitude,[4] type of instrumentation,[5–9] combined approach,[10] and decreased spinal cord perfusion due to hypotension and/or significant hemorrhage.[11–13] Procedures associated with high risk include osteotomy and kyphosis correction. The highest rates of neural injury are seen in distraction and sublaminar wire instrumentation. Decreased spinal cord perfusion may be detected intraoperatively as neural monitoring signal changes, or after surgery as delayed onset loss of neural function.

The incidence of neural complications for spinal deformity surgery has been estimated by the Scoliosis Research Society as <1%,[2,14] except when a combined approach is used, where the rate increases to 1.87%.[10] The Scoliosis Research Society database, and other organizational databases, are retrospective, nonconsecutive, and rely on voluntary reporting. In addition, they are not limited *a priori* to children or to the specific diagnosis of adolescent idiopathic scoliosis. We report on neural complications in a prospective and consecutive cohort study of 1301 children undergoing spinal fusion and instrumentation for adolescent idiopathic scoliosis.

Materials and Methods

Study Population. The principal goal of the Prospective Pediatric Scoliosis Study (PPSS) is to evaluate surgical treatment of adolescents with idiopathic scoliosis in a prospective, multicenter, and consecutive clinical series. The PPSS has been enrolling consecutive surgical patients with adolescent idiopathic scoliosis since March 2003 and continues to enroll new subjects and longitudinally follow-up currently enrolled subjects. A total of 1301 patients have been enrolled at 28 centers. A nonenrollment form is completed on patients who are not entered consecutively. This study received IRB approval from the University of California San Francisco Committee on Human Subjects Research, and all participating centers in the Spinal Deformity Study Group had IRB approval.

Inclusion criteria are thoracic, thoracolumbar, and/or lumbar idiopathic scoliosis, in patients 8 to 18 years at diagnosis and under 21 years at operation. Clinical, radiographic, and outcomes data are collected before operation and after operation at 4 to 16 weeks, 1 year, 2 years, and 5 years. All compli-

cations detected at or after operation are documented for each case. Radiographic measurements are collected electronically by trained reviewers who upload radiographic images and use specially designed software to calculate all values.

Surgeon Population. The majority of members in the Spinal Deformity Study Group are full-time academic surgeons. Those in principally private practices are affiliated with a university. Participation in the study requires entry of at least 10 cases *per annum*.

Materials. Approval was obtained from the Committee on Human Research at University of California San Francisco, and from the Research Committee of the Spinal Deformity Study Group, which maintains the PPSS database. We reviewed data for the 1301 consecutive surgical cases in the PPSS database by August 2006 for incidence of neural complications. An additional, detailed medical record review of surgical and clinical information was conducted in cases identified as having a neural complication, in order to better understand the nature of the complication.

Statistical Analyses. Incidence was calculated as the number of neural complications recorded divided by the number of patients who were at risk for neural complications from spinal operation. Cohort demographic, clinical, and radiographic characteristics were aggregated using summary statistics, while differences between those patients with neural complications and those without neural complications were analyzed using Pearson's χ^2 statistic for categorical variables and ANOVA for continuous variables. Data were analyzed using SPSS software, version 12.0 (Chicago, IL).

■ Results

Of the 1301 children who underwent spinal fusion and instrumentation for adolescent idiopathic scoliosis, there were 9 neural complications: 3 thecal penetrations, 2 nerve root injuries, and 4 spinal cord injuries.

Of the 3 thecal penetrations, 2 resulted from too medial placement of a pedicle screw and 1 resulted from dissection during surgical approach. All were treated with application of local dural sealant, and none demonstrated intraoperative neural monitoring changes or postoperative clinical sequelae.

Of the 2 nerve root injuries, 1 was a positional femoral neurapraxia from direct peripheral compression. After operation, the patient demonstrated 2/5 quadriceps femoris function, which recovered spontaneously by the 6-month postoperative evaluation. In the other case, a reduction of motor-evoked potentials in tibialis anterior on the curve concavity side lead was noted during wound closure. The lowest instrumented vertebra was L1, and the time elapsed between instrumentation and reduction was approximately 65 minutes. After operation, tibialis anterior was 3/5, and the patient complained of L4 dysesthesia, which were observed and which resolved spontaneously by the 12-week postoperative visit.

Of the 4 spinal cord injuries, the first case was a spinal fusion from T2–T12 with a 25% reduction in sensory and motor-evoked potentials at the time of placement of the concave rod. Anchors consisted of inferior pedicle screws, superior pedicle and transverse process hooks, and 2 apical sublaminar wires. With spinal reduction, which consisted of rod rotation, apical translation, together with concavity distraction and convexity compression, all signals were lost. The implants were removed and the spine was allowed to return to the position of postural reduction. Hooks and screws were reinserted and tightened to the rods *in situ*. By conclusion of the procedure, motor-evoked potentials returned but sensory evoked potentials remained depressed. After operation, the patient complained of bilateral sole hypesthesia that resolved spontaneously over 8 weeks.

The second case occurred during a posterior spinal fusion with definitive instrumentation that was performed 1 week after a same-day anterior fusion followed by posterior instrumentation with insertion of 2 temporary distraction rods for a 115° thoracic curve and an 85° lumbar curve. Both procedures were augmented with skeletal traction *via* Gardner-Wells tongs, which remained during the intervening week. Anchors included lumbar and low thoracic pedicle screws, apical lumbar and thoracic sublaminar wires, and superior thoracic pedicle and transverse process hooks. After placement of the anchors, motor- and sensory-evoked potentials were reduced on the left lumbar concave side. Intraoperative fluoroscopy showed implants in correct location. Anesthesia was lightened for a wake-up test, at which point signals returned. After operation, the patient had diffuse hypesthesia and weakness in the left lower limb, which was observed and resolved spontaneously by 8 weeks.

The third case of spinal cord injury showed normal motor- and sensory-evoked potentials throughout a T5–L3 posterior spinal fusion with all pedicle screw instrumentation. The surgical and anesthetic records noted no unusual events. After operation, however, the patient had left greater than right diffuse hypesthesia and weakness. These resolved spontaneously by 12 weeks.

In the fourth case of spinal cord injury, a posterior spinal fusion with hybrid instrumentation was performed with hooks at the cranial end, lumbar pedicle screws, and apical sublaminar wires, in that order. After passage of sublaminar wires and application of a translational reductive force, neural signals became depressed and repeated wake-up tests showed no lower limb motion. Abnormal neural signals and wake-up test remained despite relaxation of spinal reduction. Recovery occurred only after removal of all implants. The patient was fused *in situ* and after surgery braced. In none of the spinal cord injury cases was there prolonged hypotension below a mean arterial pressure of 60 mm Hg, or excessive hemorrhage (>2000 mL).

There were no cases of upper limb neurapraxia in the PPSS database.

The patients with neural complications were compared with those patients without neural complications in the PPSS database. Given the infrequency of the neural complications, we had insufficient power at the 0.8 level

Table 1. Demographic, Operative, and Radiographic Variables by Neural Complication Status

	Neural Complications (n = 9) (mean ± SD)	No Neural Complications (n = 1292) (mean ± SD)	*P*
Demographics			
Age	14.1 ± 1.5	14.3 ± 2.1	0.976
Gender: male [n (%)]	0 (0)	236 (21.9)	0.105
BMI	21.5 ± 3.6	21.5 ± 4.8	0.981
Operative			
Blood loss			0.344
Anterior	NA	433.3 ± 410.2 (n = 219)	
Posterior	1042.9 ± 694.3 (n = 9)	881.5 ± 690.1 (n = 1073)	
Total anesthesia time (min)	361.3 ± 71.9	362.0 ± 101.4	0.912
Radiographic measures			
Coronal preoperative			
Proximal thoracic	25.3 ± 9.1	23.6 ± 12.1	0.704
Main thoracic	21.6 ± 57.4	47.6 ± 31.0	0.241
Thoracolumbar/lumbar	44.1 ± 19.8	39.9 ± 13.4	0.383
Coronal balance	21.4 ± 15.2	18.8 ± 17.0	0.674
Sagittal preoperative			
T2–T12	32.3 ± 13.5	30.4 ± 14.7	0.718
T2–T5	9.8 ± 6.7	10.3 ± 8.3	0.855
T5–T12	22.8 ± 12.3	22.7 ± 14.0	0.992
T10–L2	−2.3 ± 7.0	−1.7 ± 12.1	0.902
T12–S1	−65.3 ± 11.8	−59.2 ± 13.7	0.217
Sagittal balance	12.5 ± 41.1	17.1 ± 33.6	0.699
Coronal postoperative			
Proximal thoracic	16.3 ± 8.7	13.8 ± 9.2	0.431
Main thoracic	22.4 ± 14.5	19.1 ± 11.4	0.424
Thoracolumbar/lumbar	15.4 ± 18.5	14.5 ± 10.5	0.899
Coronal balance	15.9 ± 7.5	15.4 ± 12.3	0.911
Sagittal postoperative			
T2–T12	27.1 ± 8.4	31.3 ± 12.6	0.352
T2–T5	7.5 ± 10.2	12.7 ± 8.6	0.091
T5–T12	22.8 ± 11.2	21.5 ± 10.4	0.740
T10–L2	−6.6 ± 10.6	−1.7 ± 10.9	0.203
T12–S1	−54.9 ± 7.7	−55.2 ± 13.0	0.938
Sagittal balance	22.1 ± 35.7	6.2 ± 37.0	0.225

NA indicates not applicable.

to show statistically significant differences in age, gender, curve type, preoperative and postoperative coronal or sagittal curve magnitude, or estimated blood loss (Table 1). There was sufficient power to show a statistically significant ($P = 0.034$) association between neural injury and use of sublaminar wires (Table 2).

■ Discussion

Our overall neural complication rate was 0.69%. If the dural tears are eliminated, as they imply intraspinal entry but not neural injury, together with the positional neurapraxia, which is remote from the surgical field, our complication rate is 0.38%. These findings are consistent with those of other studies.

One spinal cord injury occurred despite normal neural signals throughout the procedure. One nerve root injury was remote from the operative site, including at a level distal to the lowest instrumented vertebra. In neither patient was there a prolonged period of hypotension or excessive hemorrhage. These cases suggest a neural injury due to stretch resulting from large reductions by all pedicle screw constructs. This provides a cautious reminder of the power of modern instrumentation techniques.

Table 2. Instrumentation Used in Nerve Root and Spinal Cord Injuries

	Nerve Root/Spinal Cord Injuries (n = 5) [n (%)]	All Other PPSS Subjects (n = 1296) [n (%)]	*P*
No wires	2 (40)	1084 (83.6)	0.034
Sublaminar wires	3 (60)	212 (16.4)	

Our study was sufficiently powered (at 0.8 level) to show a statistically significant ($P = 0.034$) association between neural injury and use of sublaminar wires. Three of the 5 neural injury cases were in patients whose constructs included apical sublaminar wires. While this does not demonstrate necessarily cause and effect, our results echo those of previous studies of this implant type, 1 of which showed a neural complication rate as high as 17%.[9,15] However, other studies have disputed this finding.[16,17] Regardless of the controversy, the experience with sublaminar wires has been 1 of the factors leading toward implants that anchor outside of the vertebral canal, including pedicle screws and transverse process wires.[18]

Direct neural injury was not associated with pedicle screw fixation *per se*, which is supported by the increasing experience with this implant type for the surgical treatment of adolescent idiopathic scoliosis.[19] Having said this, 2 of the 3 dural penetrations resulted from too

medial placement of pedicle screws, as has been seen in other studies.[20] This illustrates the fact that while pedicle screw fixation is extracanal, there is a steep learning curve. However, just as hooks and wires may be placed safely in the sublaminar or circum-pedicular position, and therefore partially within the vertebral canal, there is room for pedicle perforation without neural consequence. Indeed, there may be as much if not more of a safety margin medial to the pedicle than lateral, where the great vessels and viscera may be impacted by an extraosseous screw tip.

Findings that characterized 2 of the 3 patients with neural injury and sublaminar wires included a curve that was noted to be "very flexible" as evidenced by a near total correction before release of reduction, and preoperative severe curvature that resulted in a large absolute degree of correction. The latter patient also underwent significant distraction as part of spinal reduction, including temporary distraction rods and skeletal traction.

We did not have sufficient power to detect a statistically significant difference between neural complication cases and the rest of the patients in the PPSS database. For 0.8 power, we need a minimum 48 cases of neural complication to detect statistical significance at the 0.05 level for degree of correction, and 183 cases for estimated blood loss. Age, gender, and surgical approach were so similar that the minimum number of cases necessary would be an order of magnitude higher.

There were no permanent neural injuries. This differs from the literature, which may be generally summarized as showing that incomplete spinal cord injury has a better prognosis for recovery than complete injury, and that recovery is approximately full in one third, partial in one third, and absent in one third of affected patients.[2] Our findings may be explained in several ways. First, the number of events is relatively small. Second, none of our spinal cord injuries was complete. Third, all cases employed intraoperative neural monitoring, including somatosensory and motor-evoked potentials, as well as electromyography, which allows for rapid response to neural change. Fourth, we may be reflecting the resilience of a specifically pediatric population and a specific diagnosis of adolescent idiopathic scoliosis, in contrast with other studies that have included adults as well as children, and varied diagnoses (such as congenital and neuromuscular spinal deformity).

Because this is a study of neural complications, follow-up time was determined by outcome, and there was no loss to follow-up. Since every patient had complete resolution—the longest period being at the 6-month check for a girl with femoral neurapraxia—this was determined to be the length of follow-up necessary. This differs from other outcome studies, where many factors may degrade with time, and where long-term follow-up is necessary to capture this phenomenon.

A fundamental concern of any study reporting neural complications, on account of their gravity, is under or incomplete reporting. Because of this, the Spinal Deformity Study Group has assembled a subcommittee to perform regular random reviews to ensure the quality of data in the PPSS database. We recently performed the first such review, without detecting any error. The study is prospective and consecutive, which reduces selection bias. In addition, the list of neural complications in our data collection forms is extensive and consistent with literature, and is listed in Table 3. Finally, there are multiple checks of the validity of reporting: the study forms are filled out by surgeon and a designated site-specific research coordinator, and follow-up evaluations often include attending and resident surgeons as well as surgeon extenders, such as physician assistant and clinic nurse, all of which aid in completeness and retention.

Table 3. Neural Complications in the Prospective Pediatric Scoliosis Study

Cerebrospinal spinal fluid leak
Cauda equina syndrome
Nerve root injury
Postoperative radiculopathy
Spinal cord injury
Somatosensory-evoked potential changes
Motor-evoked potential changes
Electromyographic changes
Wake-up test change

The preoperative workup of children enrolled in the PPSS includes history, physical examination, and roentgenographic assessment of spinal deformity. A preoperative spinal MRI was obtained at the discretion of the surgeon. In a follow-up study we performed on the same cohort of patients, we found the rate of preoperative MRI to be 40%. Factors associated with obtaining an MRI were age under 10 years, thoracic kyphosis >40°, male gender, and obesity. Other signs of "atypia," in particular significant neural abnormality, would exclude a patient from a study of "idiopathic" scoliosis.

The following themes emerge from our cases. First, large reduction may result in injurious neural stretch, including remote from the operative site. Second, apical sublaminar wires may carry an increased risk of neural injury. Third, neural injury remains a real, albeit low, risk of the surgical treatment of adolescent idiopathic scoliosis. There seems to be a "floor effect" with regard to neural complications: while our database is supplied by spinal surgeons with extensive experience, the rate of this complication remains similar to historical controls. While our surgeons may be more familiar and comfortable and therefore "safer" in operating on the spine and with current instrumentation techniques, these very systems perhaps have emboldened surgeons to exert greater influence on the deformed spine (*e.g.*, increasing number of anchors, more widespread use of adjunct procedures, such as spinal osteotomy) in order to improve correction, to return patients to activity sooner, to forego the need for postoperative bracing, and to improve fusion rates.

Our study has the distinct advantages of being the first prospective and consecutive and pediatric-specific as

well as diagnosis-specific assessment of the neural complications of surgical treatment of adolescent idiopathic scoliosis. Its greatest limitation is that it remains underpowered at the current number of neural complications for total size of database. However, this limitation underscores the safety of this surgical treatment in this population. In addition, the limitation will be addresses as we continue to evaluate and report on this extremely important aspect of spinal surgery.

■ Key Points

- Of 1301 consecutive spinal fusions with instrumentation for adolescent idiopathic scoliosis, there were 9 neural complications identified, for a rate of 0.69%.
- Neural stretch and sublaminar wires may be risk factors.
- None of the neural complications was permanent; all resolved completely within 6 months of primary operation.

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