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Outcomes of instrumented fusion in the pediatric cervical spine

Clinical article

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Object. The most common cause of cervical spine arthrodesis in the pediatric population is instability related to congenital or traumatic pathology. Instrumenting the cervical spine can be challenging given smaller anatomical structures, less ossified bone, and future growth potential and development. Studies in adult patients have suggested that using screw constructs results in improved outcomes with lower rates of instrumentation failure. However, the pediatric literature is limited to small retrospective series. Based on a review of the literature and their own patient series, the authors report that instrumenting the pediatric cervical spine with screw constructs may be safer and more effective than using wiring techniques.

Methods. The authors reviewed the existing pediatric cervical spine arthrodesis literature and contributed 31 of their own cases from September 1, 2007, to January 1, 2011. They reviewed 204 abstracts from January 1, 1966, to December 31, 2010, and 80 manuscripts with 883 total patients were included in the review. They recorded demographic, radiographic, and outcomes data—as well as surgical details—with a focus on fusion rates and complications.

Patients were then grouped into categories based upon the procedure performed: 1) patients who underwent fusions bridging the occipitocervical junction and 2) patients who underwent fusion of the cervical spine that did not include the occiput, thus including atlantoaxial and subaxial fusions. Patients were further subdivided according to the type of instrumentation used—some had posterior cervical fusion with wiring (with or without rod implantation); others had posterior cervical fusion with screws.

Results. The entire series comprised 914 patients with a mean age of 8.30 years. Congenital abnormalities were encountered most often (in 55% of cases), and patients had a mean follow-up of 32.5 months. From the entire cohort, 242 patients (26%) experienced postsurgical complications, and 50 patients (5%) had multiple complications. The overall fusion rate was 94.4%.

For occipitocervical fusions ($N = 285$), both screw and wiring groups had very high fusion rates (99% and 95%, respectively, $p = 0.08$). However, wiring was associated with a higher complication rate. From a sample of 252 patients, 14% of those treated with screw instrumentation had complications, compared with 50% of patients treated with wiring ($p < 0.05$).

In cervical fusions not involving the occipitocervical junction ($N = 181$), screw constructs had a 99% fusion rate, whereas wire instrumentation only had an 83% fusion rate ($p < 0.05$). Similarly, patients who underwent screw fixation had a lower complication profile (15%) when compared with those treated with wiring constructs (54%, $p < 0.05$).

Conclusions. The results of this study are limited by variations in construct design, use of orthoses, follow-up duration, and newer adjuvant products promoting fusions. However, a literature review and the authors' own series of pediatric cases suggest that instrumentation of the cervical spine in children may be safer and more efficacious using screw constructs rather than wiring techniques.

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Key Words • **pediatric** • **arthrodesis** • **instrumented fusion** • **cervical spine** • **occipitocervical**

Cervical spine arthrodesis is typically used in the pediatric population when a patient has instability related to congenital or traumatic pathology. The etiology of mechanical instability includes trauma, os odontoideum, infection, atlantoaxial rotatory subluxation, juvenile rheumatoid arthritis, Down syndrome, mucopolysaccharidoses, spondyloepiphyseal dysplasia, iatrogenic causes, tumors, and other less common entities.[13,20,27,28,32,36,55,69,80] Although it only accounts for 1%–4% of overall spinal trauma, pediatric spinal trauma is one of the most common reasons children require cervical instrumentation.[16,49,67,69] Pediatric spinal trauma is typically localized to the cervical segment (60%–80%), with upper cervical trauma more common in younger children.[2,49,69] However, internal spinal fixation in children can be challenging given their smaller anatomical structures, reduced bone purchase, considerations for future growth potential, congenital abnormalities, and cartilaginous components of bone at younger ages.

The first reported occipitocervical arthrodesis was performed in 1927 by Foerster,[26] who used a fibular strut graft. Historically, internal instrumentation was not technically feasible in young children, so external orthosis through casting or halo-vest immobilization was employed to manage instability. However, the use of external immobilization for younger children entailed significant morbidity and still does even now.[21,54] Early surgical intervention progressed to employ Mersilene tape,[53] occipital periosteal flaps,[50] or wiring,[22] but newer instrumentation using screws allows for more rigid fixation with less morbidity.[44,70]

Wiring techniques included instrumentation of rods to the suboccipital bone; Brook, Gallie, and Sonntag fusions; and variations of graft fixation to the spinous processes, facets, and sublaminar fixation. However, use of wires was often supplemented with external orthosis, such as halo-vest immobilization, and had a relatively high complication rate. Internal fixation of the cervical spine has evolved since the use of wiring and has progressed to the use of laminar hooks and clamps and various techniques of screw fixation to each level of the cervical spine.

Transarticular C1–2 screws as described by Jeanneret and Magerl[46] provide a very rigid and biomechanically sound construct with the incorporation of 4 cortical surfaces, but the insertion procedure is technically demanding because of the danger of vertebral artery injury, especially in cases in which atlantoaxial subluxation remains irreducible preoperatively. Although successful transarticular screw fixation of the atlantoaxial complex has been extensively reported in adult series, there have been only a handful of reports in the pediatric population. Analysis of clinical experience in the largest series of pediatric patients[32] suggested a 4% rate of vertebral artery injury during screw placement; none of these injuries resulted in any long-term morbidity or mortality.

Because of the anatomical limitations complicating transarticular screw placement in adults and even more so in children, variations of C1–2 screw fixation have been reported in adult patients in whom independent C-1 lateral mass screws and C-2 pars/pedicle screws were connected with either a plate[33] or a rod.[38] Atlantoaxial screw-rod fixation has been suggested as a safer procedure, and perhaps the technique is applicable in more patients—even in the smallest of pediatric patients—despite anatomical variations.[45] It is an ideal technique to fix and reduce occipitoatlantoaxial deformities that remain irreducible with closed reduction.

Wright[86,87] described a new technique for rigid screw fixation of the axis, involving the insertion of polyaxial screws into the laminae of C-2 in a bilateral crossing fashion, and demonstrated the feasibility of this technique for the general adult population. Because the C-2 translaminar screws are not close to the vertebral artery, this technique provides a means of achieving rigid fixation of C-2 through a safer technique. Recently, teams of authors[15,52] have reported their experience with this technique of crossing and noncrossing screws in small series of children.

Although lateral mass screw fixation in the cervical spine has been shown to provide excellent stability and high rates of fusion in adult patients, little has been published about the use of subaxial lateral mass screws in the pediatric age group. Moreover, no cadaveric biomechanical data are available with respect to the use of these types of constructs in the pediatric cervical spine.

The two most popular techniques for insertion of lateral mass screws are the Roy-Camille and Magerl techniques. However, nerve roots, vertebral arteries, facet joints, and the dura and spinal cord are at risk during the placement of lateral mass screws. A recent review of the literature[3] indicated that the youngest patient in whom subaxial lateral mass screws were successfully used was 8.2 years old. This correlates with the age at which most authorities agree that the developing spine takes on an "adult" configuration.[4,12] Despite this, the authors were only able to place 3.5 × 10–mm screws—the shortest screw length that is manufactured. Although a solid fusion was achieved in this case after 3 months of rigid immobilization, another study[76] of predominantly adult patients has suggested that a minimum subaxial lateral mass screw length of 14 mm is needed to confer any substantial degree of biomechanical stability.

Pedicle screw fixation systems have been widely used for reconstruction of the thoracic and lumbar spine because of their biomechanical superiority. Abumi and colleagues[1,2] reported clinical results of pedicle screw fixation for reconstruction of traumatic and nontraumatic lesions of the middle and lower cervical spine. However, use of the procedure in the upper cervical spine has been criticized due to the potentially high risk to neurovascular structures, except at the C-2 level.

Continuous advances in technology and technique have increased the safety of cervical spine surgery and have improved surgical outcomes. Rigid internal fixation often permits stabilization without external immobilization, enables more rapid recovery and rehabilitation, and eliminates the risks associated with external orthoses.[39] Previously, pediatric spine surgeons were limited by a lack of appropriately sized instrumentation and, thus, either adapted adult-sized tools or used wiring techniques to stabilize the spine.[17] Recent developments in instrumentation and techniques for the craniocervical junction and subaxial cervical spine include occipital screws, C-1 lateral mass screws, C1–2 transarticular screws, axial and subaxial translaminar screws, C-2 pedicle/pars screws, and subaxial cervical pedicle screws.[17] However, using cervical spine instrumentation with screws in the pediatric population is a relatively new technique, and outcomes are not thoroughly understood, given the paucity of cases in the literature. The results of studies in adults have suggested that screw constructs improve outcomes, with lower rates of instrumentation failure,[85] but the pediatric literature is limited to small retrospective series.

To better understand the risks and outcomes of instrumented spine surgery in the pediatric population, we reviewed the literature and compared types of fixation used in the cervical spine. Furthermore, we reviewed our own series of 31 cases involving pediatric patients and contribute our data to the literature.

Methods

We performed PubMed and OVID searches using the key words "pediatric cervical fusion," "pediatric craniocervical," "pediatric occipitocervical," "pediatric atlantoaxial," "spinal fusion," "cervical spine," and "occipitocervical." Criteria included articles from peer-reviewed journals that described an instrumented cervical fusion in pediatric patients (age < 18 years) and reported either fusion rates by radiological evaluation at more than 3 months' follow-up or complications associated with the procedures. Given that there is variability in the accepted definition of a successful fusion and a lack of CT imaging in early studies, we included 3 categories of presumed osseous fusion based on prior publications: 1) CT-corroborated evidence of osseous fusion, 2) stability on flexion-extension radiographs, and 3) authors' presumption of successful fusion on the basis of plain radiographs. Exclusion criteria were as follows: 1) articles published in any language other than English, 2) patients older than 18 years at the time of surgery, 3) noninstrumented cervical fusions, 4) studies not reporting either complications or fusion rates, 5) studies reporting successful outcomes using other parameters than those 3 listed previously, and 6) larger studies in which we were unable to identify outcomes of interest for a subgroup of patients fulfilling our criteria. Fusion constructs that were primarily thoracolumbar were excluded, and only those primarily cervical and spanning at most a few upper-thoracic segments were included. References in identified papers were manually cross-referenced, and additional articles meeting the criteria were added to the literature review.

We reviewed 204 abstracts dating from January 1, 1966, to December 31, 2010. A total of 883 patients in 80 articles were included in the review. Data collected included patient age, patient sex, etiology of cervical instability, procedure performed, levels fused, construct materials, graft type, adjunct biological compound, postoperative orthosis, follow-up duration, fusion rate, method of evaluation of fusion, and complication type and frequency. Fusion rates were only recorded when the article stated that solid fusion was identified radiographically per our criteria and with at least 3 months of follow-up. Complications were only recorded if they were reported or if the authors explicitly stated that no complications occurred within their series. We also collected similar demographic, radiographic, and clinical measures on our series of 31 patients who underwent instrumented cervical fusion procedures performed by members of the Neuro-Spine Program at Texas Children's Hospital between September 1, 2007, and January 1, 2011.

Patients were then grouped into 3 categories based upon the procedure performed. One cohort encompassed patients who underwent fusions bridging the occipitocervical junction; a second cohort represented patients who underwent fusion of the cervical spine that did not include the occiput, but included atlantoaxial and subaxial fusions; a final group consisted of A) the studies with a combination of procedures where insufficient data were provided to divide the patients into the aforementioned subgroups and B) miscellaneous studies with insufficient numbers to analyze independently and adequately (anterior fusions, hook constructs, mixed constructs). The first 2 groups were further subdivided according to the type of instrumentation used. Patients were categorized as having either posterior cervical fusion with wiring (with or without rod implantation) or posterior cervical fusion with screws.

Statistical analysis was performed using the Student t-test and chi-square analysis using Microsoft Excel and GraphPad Instat 3 software. If the sample size was insufficient for chi-square testing (N < 5), the Fisher exact text was used or a Yates correction was adopted. A p value of 0.05 was considered statistically significant.

Results

Entire Cohort

The entire cohort was composed of 883 patients in 80 series along with our own 31 patients. The total number of patients was 914, with the average number of patients in a single series being 8.6 (range 1–96). In the 72 series that specified sex data, 279 patients (44%) were female and 357 male (56%). The mean age was 8.30 years. The etiologies encountered most often were congenital abnormalities (55%) followed by trauma (27%); Down syndrome (9%); and infectious, oncological, iatrogenic, or miscellaneous causes (9%). The use of demineralized bone matrix was reported in 4 series; the use of bone morphogenetic protein was reported in 2 series. The use of adjuvant external orthosis was inconsistently reported; therefore, it was impossible to further analyze its impact on fusion rates and outcomes. The mean duration of follow-up was 32.5 months. From the entire cohort, 242 patients (26%) experienced postsurgical complications, and 50 (5%) had multiple complications. The overall fusion rate based on the 3 criteria was 94.4%.

Occipitocervical Fusion

We assessed occipitocervical fusions from 29 articles included for this purpose (Fig. 1, Table 1). Ten reports featured instrumentation with primary screw constructs (combinations of occipital screws; C-2 pars, C-2 translaminar, C1–2 transarticular screws; and atlantal and subaxial lateral mass screws). In these 10 papers, there were 137 patients and we added 20 of our own—with a mean age of 7.6 years, and they constituted the OC screw group. The remaining 19 papers reported on fusions in which wires were primarily used, with additional implantation of rods in 10 of the reports. These 19 papers reported on a total of 128 patients (mean age 8.8 years), who constituted the OC wire group.

In 85% of the cases in which occipitocervical screw fusion was used (OC screw group) the instrumentation ex-

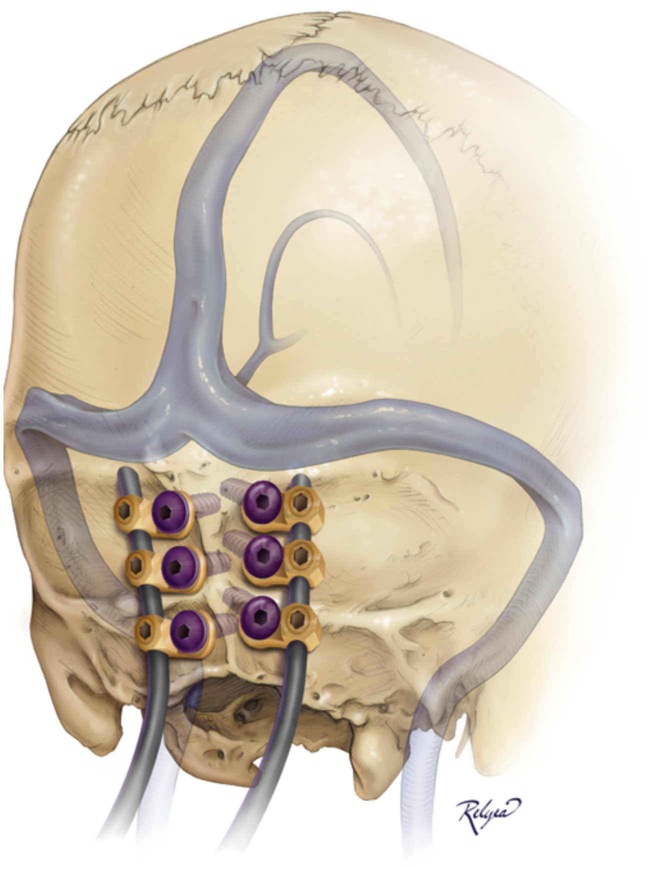

Fig. 1. Illustration of occipitocervical fusion by Katherine Relyea.

tended to C-2 (Fig. 2); in only 3 cases (2%), instrumentation extended to the thoracic spine. The overall range for the group was C-1 to T-5. In the majority of cases, autograft was obtained from either rib or iliac crest (85%), and 5 papers reported adjunctive use of bone morphogenetic protein or demineralized bone matrix. The majority of papers (72%) reported use of some external orthosis as well, varying from a rigid collar to halo immobilization. In almost every reported case (99%) there was successful fusion by 3 months with a mean follow-up of 20.4 months.

Of the group of patients treated with occipitocervical fusion using wires (OC wire group), 45% (58 patients) had instrumentation extending to C-2 and in 37% it extended to C-3. All fusions extended to at least C-2, and the most caudal extent reported was to T-4. Fusions extended to the thoracic spine in only 3 cases. In 2 papers, the use of bone graft was not reported, but the remaining 17 all used autogenous bone graft. External orthoses were used in all reported cases but one; halo immobilization was employed in the majority (84%). Successful fusion was achieved in 95% of cases with a mean follow-up of 42.1 months.

Both groups had very high fusion rates (99% and 95%, respectively), and although there was a no statistically significant difference ($p = 0.08$), there was a trend favoring the use of screws.

Complications With Occipitocervival Fusions

Only 7 papers with 116 patients from the OC screw group had sufficient data to evaluate associated complications (Table 2). The addition of 20 patients from our own experience brought the total to 136. The mean patient age was 7.3 years, and the mean duration of follow-up was 20.1 months. Complications included infection, hematoma, vascular injury, screw pullout, nonunion, instrumentation malposition, transient vocal cord paresis, dysphagia, intraoperative CSF leak, transverse sinus injury, and transient dysphagia. Nineteen patients (14%) experienced 24 complications. Four patients suffered multiple complications. All CSF leaks noted in this group were intraoperative and did not require any further intervention; all neurological changes were transient.

Patients from 16 papers (total of 116 patients, mean age 9.3 years, mean follow-up 46.8 months) were included in the OC wire group. Complications in this group included those mentioned previously but also involved resorption of graft, unintended extension of fusion mass, pneumonia, hydrocephalus, instrumentation failure, respiratory compromise, facial cellulitis, death, and quadriparesis. Several of the reported CSF leaks in the OC wire group required reoperation, including, in 2 cases, implantation of a lumboperitoneal shunt. Fifty-eight patients (50%) had a total of 85 complications. Twenty-three patients had multiple complications. There was a statistically significant difference in the number of patients who had screw construct complications and those who had wire construct complications ($p < 0.05$).

Cervical Spine (Excluding Occipitocervical Junction)

Twenty-seven articles fulfilled criteria to assess fusion rates of pediatric cervical spine instrumentation excluding the occipitocervical junction (Table 3). Of these articles, 13 addressed fusions using primarily screw instrumentation (cervical screw group), and the remaining 14 involved wires (cervical wire group). Ten cases from our own experience were added to the cervical screw group and one to the cervical wire group. The cervical screw group included patients with C-1 lateral mass fixation, C-2 pars screws, C-2 pedicle screws, C1–2 transarticular screws, subaxial lateral mass plates and screws, C-2 translaminar screws, and 2 series each supplementing transarticular screws with wires or a C-1 hook (Fig. 3). The cervical wire group included variations of sublaminar and spinous process wiring as described by Gallie, Brooks, and Sonntag (Fig. 4).

The cervical screw group comprised 79 patients with a mean age of 10.2 years. The majority (97%) involved atlantoaxial fixation, although in 1 case instrumentation extended to T-2. One paper did not specify whether bone graft was employed; in the remaining papers autograft was used to varying extents. The authors of 10 articles reported using postoperative orthoses—mostly rigid cervical collars. Only 1 patient did not have a bony fusion. Overall, 99% of patients had a successful fusion with a mean follow-up of 16.7 months.

The cervical wire group was composed of 118 patients with an average age of 9.4 years. Of the patients, 51% had fusions only involving the atlantoaxial levels, and C-6 was the most caudal extent of instrumentation. In the majority of papers (67%) autograft was used; in the remaining ones either allograft was used or the authors did

TABLE 1: Fusion rates in patients treated with occipitocervical constructs*

Authors & Year	No. of Pts	Sex Ratio (F/M)	Mean Age (yrs)	Construct Details	FU (mos)	Fusion Rate	Fusion Criteria†
Brockmeyer & Apfelbaum, 1999	10	1:09	8.8	TAS, OMI construct, cables, couplers, O screws	18.8	10/10	1
Schultz et al., 2000	1	0:01	11.9	C-1 plates, C-2 pars screws, C-3 LMS	52	1/1	2
Meyer et al., 2001	1	0:01	15	O–C2 TAS; O–C2 midline wiring	48	1/1	2
Garg et al., 2003	1	0:01	10	O screws, LMS, plate/rods	24	1/1	3
Anderson et al., 2007	19	10:09	9.1	screws & rods/loops/plates	17.5	17/17	1 or 3
Haque et al., 2009	4	NA	10.5	C-3 LMS, C-2 pars, translaminar screws	13.5	4/4	1
Bisson et al., 2010	1	1:00	16	O plate, C-1 LMS, C-2 pars, C-3 LMS	12	1/1	3
Couture et al., 2010	22	7:15	4.9	Wasatch plate, C-2 pars, TAS, translaminar screws	48.2	22/22	1
Hankinson et al., 2010‡	16	NA	7.7	O screws, C-2 pars, laminar screw	14.2	16/16	1
	22	NA	5.4	O screws; C-1 & C-2 screws	14.2	20/20	1
	39	NA	8.3	O screws, C1–2 TAS	14.2	39/39	1
Jeszenszky et al., 2010	1	0:01	11	O plate, C-1 LMS & rods	108	1/1	1
present paper	20	10:10	7.7	O screws, pars, LMS screws, pedicle screws	11.61	17/18	1
(The articles listed in the upper part of the table represent primary screw constructs; the lower part, primary wiring techniques.)							
Segal et al., 1991	6	3:03	10.4	wires	26.7	4/6	2
Dormans et al., 1995[22]	16	4:12	9.5	Luque loop rod & wires	37	15/16	3
Nakagawa et al., 1997	8	7:01	8.3	Hartshill, wires	70.8	8/8	3
Rodgers et al., 1999	23	16:07	8	O wires to K wire in spinous process, distal sublaminar wires	69.6	22/23	2
Schultz et al., 2000	10	6:04	8.2	OC loop	21.2	9/9	2
Meyer et al., 2001	2	2:00	5.5	midline wiring	26.5	2/2	2
Banks et al., 2003	1	0:01	13	loop w/ wires (anterior support)	9	1/1	3
Visocchi et al., 2009	6	6:00	9.5	titanium rod, sublaminar wires	63	5/6	1
Dickerman et al., 2005	1	1:00	1.5	rod w/ wires, graft w/ sublaminar wires	4	1/1	1
Roy & Gibson, 1970	6	NA	5.6	wires	NA	4/6	3
Koop et al., 1984	1	0:01	7.6	wires	11.75	1/1	2
Letts & Slutsky, 1990	7	1:06	9.3	wiring or suture	58.8	7/7	3
Casey et al., 1995	7	4:03	6.5	sublaminar wires	NA	7/7	2
Higo et al., 1995	4	3:01	6.8	Luque loop rod & wires	19.3	4/4	3
Tuite et al., 1996	16	9:07	11.6	cable, wire, Ransford loop (anterior support)	53.4	16/16	1
Houle et al., 2001	1	0:01	13	Locksley bar & wires	6	1/1	3
Kim et al., 2004	11	4:07	8.7	wires & Steinmann pins	39.4	11/11	2
Tubbs et al., 2002	1	1:00	2	loop & cable	2	1/1	3
Yamazaki et al., 2006	1	1:01	7	loop & wires	12	1/1	3
total						120/126	

* FU = follow-up; LMS = lateral mass screws; NA = data not available; O = occipital; OC = occipitocervical; Pts = patients; TAS = transarticular screws.

† Fusion criteria were defined by 3 categories after 3 months of follow-up: 1) CT-corroborated evidence of osseous fusion, 2) stability on flexion-extension radiographs, and 3) the authors' presumption of successful fusion on the basis of plain radiographs.

‡ The 3 entries represent a breakdown of 1 publication.

not specify the source of bone graft. One paper did not report use of external orthoses, but in all other patients some type of postoperative external support was used, with 47% favoring halo immobilization. In this group, 83% of patients achieved a successful fusion with a mean follow-up of 94.5 months.

The difference in fusion rates between the two groups was significant ($p < 0.05$) in favor of the cervical screw group.

Complications With Cervical Spine Fixation Excluding the Occipitocervical Junction

Data from 61 cases reported in 11 articles were used to examine complications associated with cervical fusion excluding the occipitocervical junction (Fig. 5, Table 4). To this group were added 10 cases from our own series. The mean age of the patients in these 71 cases was 10.3 years (mean follow-up 17.8 months). Of the cohort, 11 patients (15%) experienced 12 different complications; 1

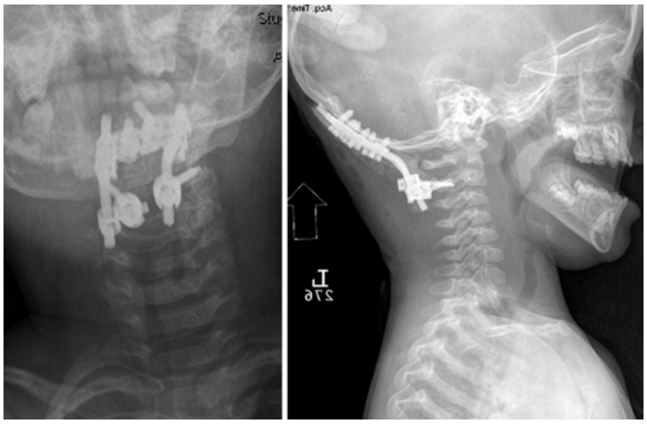

Fig. 2. Anteroposterior **(left)** and lateral **(right)** radiographs showing an occipitocervical fusion in a 2-year-old girl involved in a motor vehicle accident with occipitoatlantal instability.

patient had 2 complications. The complications included transient paresthesias, unintended extension of fusion, donor-site graft pain, kyphotic deformity, infection, pseudarthrosis, and rod migration.

An additional 100 cases were reported in 10 articles that assessed complications among patients who underwent cervical fusions with placement of wires not involving the occipitocervical junction (cervical wire group). We contributed 1 additional case from our series. The mean age of this patient cohort was 9.0 years (mean follow-up 101.4 months). Complications in this group were more severe than in the previously described group and included death, graft resorption, quadriparesis, transient radiculopathy, pseudarthrosis, spinal cord injury, infection, wire migration, seroma, CSF leak, and mechanical instability. Fifty-five patients (54%) had 61 complications; 7 patients had multiple complications. The difference in complication rates between patients treated with wires and those treated with screws was statistically significant ($p < 0.05$).

Discussion

Instrumenting the cervical spine in the pediatric population continues to present challenges to surgeons. Children have smaller anatomical structures, increased segmental motion, increased ligamentous laxity, and less ossified bone; additionally, fusions must still permit growth and development. Furthermore, many pediatric patients requiring a cervical fusion have congenital syndromes and frequently have concurrent osseous, neurological, or vascular anatomical abnormalities. As a successful fusion requires immobilization of desired segments with a bone graft under compression, immobilization via rigid internal screw constructs appears advantageous.[9] Screw instrumentation constructs have superior biomechanical stabilization compared with wiring techniques,[34,59,64,79] but little data exists in the literature regarding their application and outcomes in pediatric patients. We pooled available data in the literature and added data from our own series to investigate outcomes of cervical instrumentation in the pediatric population.

The overall fusion rate for our series was 94.4%, but significant differences were noted between instrumentation based primarily on the use of screws and wire constructs. In the occipitocervical cohort, fusion rates were both very high (99% in the OC screw group, 95% in the OC wire group), and although the difference was not statistically significant ($p = 0.08$), a trend favored the use of screw fixation. Similarly, high fusion rates were described in the remaining cervical spine fusions using screws (99%), but the rate of osseous fusion was only 83% for patients treated with wire instrumentation that did not involve the occipitocervical junction. Therefore, pediatric cervical instrumentation with screws does appear to have a higher rate of fusion than wiring techniques.

Although osseous fusion is critical, the instrumentation selection must also balance the need for biomechanical stability with minimizing surgical morbidity. Of the entire cohort, 26% experienced a complication, and 5% suffered from multiple complications. In the occipitocervical groups, 14% of the OC screw cohort had complications compared with 50% with wiring ($p < 0.05$). This difference was repeated with very similar outcomes in the cohort not involving the occipitocervical junction (15% in the cervical screw group vs 54% in the cervical wire group, $p < 0.05$).

Furthermore, the complications in the screw cohorts appeared to be less severe than those in the wire cohorts. No CSF leaks from either screw cohort required further intervention, but several of the CSF leaks with wires led to wound infection, wound revision, or lumboperitoneal shunt placement. Whereas many of the neurological complications in patients treated with screws were transient, several neurological complications in patients treated with wires led to quadriparesis or death. Overall, the complications encountered with wiring techniques were more frequent and more severe.

We were unable to assess complications by instrumentation type beyond wire versus screw fixation, given a paucity of subtypes and excessive variability in surgical technique. Some authors combined multiple techniques—for example, supplementing transarticular screws with wiring. Cervical spinal fixation has progressed from wiring techniques to mostly screw-based fixation when anatomically feasible, but wiring is still used occasionally in patients who cannot tolerate screws. Patients treated with wiring generally had fusions involving more segments than patients treated with screw constructs. Few authors commented on junctional disease and preservation of adjacent levels.

McGrory and Klassen[57] followed a group of 42 patients for 7.0–40.5 years and reported a 38% rate of fusion extending beyond desired levels. Extension of fusion was evident at 2 years' follow-up, and 29% of patients had adjacent-level osteosclerotic changes, which appeared more frequently with longer follow-up. Similarly, other authors have reported high rates of undesired autofusion with long follow-up in patients treated with wires.[62,66] The longer duration of follow-up seen in both of our wiring groups may, to some degree, account for the more numerous complications encountered with wiring. However, in 2 longer-term follow-up studies using screws, the authors

TABLE 2: Complications associated with occipitocervical instrumentation*

Authors & Year	No. of Pts	Sex Ratio (F/M)	Mean Age (yrs)	FU (mos)	Complications	No. of Compls	No. of Pts w/ Compls	No. of Pts w/ Mult Compls
Brockmeyer & Apfelbaum, 1999	10	1:9	8.8	18.8	superficial wound infections, temp vocal cord paresis, screw pullout	4	3	1
Schultz et al., 2000	1	0:1	11.9	52	halo pin–site infection	0	0	0
Meyer et al., 2001	1	0:1	15	48	none	0	0	0
Belen et al., 2006	1	0:1	9	12	none	0	0	0
Haque et al., 2009	4	NA	10.5	13.5	none	0	0	0
Hankinson et al., 2010	16	NA	7.7	14.2	wound hematoma, graft harvest–site infection	2	2	0
	22	NA	5.4	14.2	VA injury, superficial wound infection, reintubation	3	2	1
	39	NA	8.3	14.2	VA injuries	2	2	0
Couture et al., 2010	22	7:15	4.9	48.2	screw pullout, screw malposition, superficial infections	5	5	0
present paper	20	10:10	7.7	11.6	transverse sinus injuries, CSF leaks, trans dysphagia, trans quadriparesis, wound infection, pseudarthrosis	8	5	2
(The articles listed in the upper part of the table represent primary screw constructs; the lower part, primary wiring techniques.)								
Koop et al., 1984	1	0:1	7.6	11.8	ext of fusion mass	1	1	0
Flint & Hockley, 1987	5	2:3	8.8	14.2	spastic quadriparesis, HC	3	3	0
Segal et al., 1991	6	3:3	10.4	26.7	quadriplegia, death, graft resorptions, wound dehiscence, infection, broken hardware	13	6	5
Smith et al., 1991	1	0:1	16	24	none	0	0	0
Dormans et al., 1995[21]	16	4:12	9.5	37	pseudarthroses, pin-site infection, facial cellulitis, unintended fusion, pneumonia	8	7	1
Higo et al., 1995	4	3:1	6.8	19.3	none	0	0	0
Tuite et al., 1996	16	9:7	11.6	53.4	dysphagia, instrumentation extrusion, trans quadriparesis, prolonged ventilation, death, brain abscess	20	10	7
Lowry et al., 1997	4	3:1	8.3	32.3	pseudarthrosis	2	2	1
Nakagawa et al., 1997	8	7:1	8.3	70.8	ext of fusion mass	5	5	0
Rodgers et al., 1999	23	16:7	8	69.6	pseudarthroses, spinous process Fx, unintentional ext of fusion, CSF leaks requiring LP shunts, trans quadriparesis, halo pin–site infections, skin breakdowns (halo vest), wound breakdown, radiculopathy, failure of instrumentation, pneumonia, HC	16	13	4
Schultz et al., 2000	10	6:4	8.2	21.2	pin-site infection, CSF leak, infection	5	2	2
Meyer et al., 2001	2	2:0	5.5	26.5	ext of fusion, neurol decline	3	2	1
Kim et al., 2004	11	4:7	8.7	39.4	infections; hyperostosis	4	3	1
Lekovic et al., 2006	1	0:1	10	192	pseudarthrosis	1	1	0
Visocchi et al., 2009	6	6:0	9.5	63	CSF leak, infection	2	1	1
Hankinson et al., 2010	2	1:1	13	13.5	respiratory compromise	2	2	0

* Compl = Complication; ext = extension; Fx = fracture; HC = hydrocephalus; LP = lumboperitoneal; Mult = Multiple; neurol = neurological; temp = temporary; trans = transient; VA = vertebral artery.

TABLE 3: Fusion rates for cervical spine instrumentation excluding the occipitocervical junction*

Authors & Year	No. of Pts	Sex Ratio (F/M)	Mean Age (yrs)	Construct Details	FU (mos)	Fusion Rate	Fusion Criteria
Brockmeyer et al., 1995	8	5:03	11.8	LMS	14.5	8/8	3
Wang et al., 1999	13	4:09	9.5	TAS	26.2	13/13	2
Sasaki et al., 2000	1	0:01	5	TAS	12	1/1	2
Meyer et al., 2001	3	1:02	13	TAS w/ wiring	17.3	3/3	2
Brockmeyer, 2002	2	2:00	1.7	TAS w/ modified Gallie wiring	7.5	2/2	1 or 3
Beiner et al., 2006	1	1:00	10	LMS & plates	36	1/1	3
Leonard & Wright, 2006	2	0:02	16	C-1 LMS & C-2 TLS	12	2/2	1 or 2
Anderson et al., 2007	6	0:06	12.7	TAS/LMS/pars/TLS	6	5/5	1 or 3
Haque et al., 2009	13	NA	9.7	C-1 LMS, C-2 pars screws, C-2 sublaminar wires	14.6	12/12	1
Heuer et al., 2009	6	4:02	12.7	C-1 LMS, C-2 pedicle screws	14.7	6/6	1 or 2
Desai et al., 2010	8	6:02	9	C-1 LMS, C-2 pedicle or C-3 LMS	23	8/8	2
Ni et al., 2010	5	1:04	10	C1–2 TAS, C-1 laminar hooks	14.4	5/5	1
Plant & Ruff, 2010	1	0:01	10	C1–2 LMS & pedicle screws	36	0/1	2
present paper	10	6:04	9.125	C-1 LMS, C-2 pars screws, LMS	11.64	10/10	1
(The articles listed in the upper part of the table represent primary screw constructs; the lower part, primary wiring techniques.)							
Dzenitis, 1966	1	1:00	13	sublaminar wires	6	1/1	2
Roy & Gibson, 1970	5	NA	11.4	Gallie	NA	3/5	3
McWhorter et al., 1976	6	3:03	5.9	spinous process wires	85.2	5/5	3
Koop et al., 1984	1	0:01	17.75	wires	7.92	1/1	2
Mah et al., 1989	14	7:07	11.8	C1–2 Gallie fusion w/ K wire in C-2 spinous process	57.6	14/14	2
Segal et al., 1991	4	2:02	6.7	modified Gallie fusion	17	0/3	2
Smith et al., 1991	17	NA	NA	sublaminar wire	25	14/16	2
McGrory & Klassen, 1994	42	14:28	12.66	wiring: interspinous, sublaminar, sublaminar sutures	210	24/31	2
Lowry et al., 1997	22	10:11	9.8	Brooks, Gallie, triple wire	12.9	19/22	2
Fuchs et al., 2001	1	1:00	14	intraspinous wiring	36	1/1	3
Heilman & Riesenburger, 2001	1	0:01	4.08	wires	36	1/1	3
Stevenson et al., 2002	1	0:01	15	Gallie at C1–2, intraspinous C2–4	38	1/1	3
Menezes, 2008	1	1:00	6	cables	48	1/1	3
Visocchi et al., 2009	1	0:01	12	Sonntag cables	46	1/1	1
present paper	1	0:01	0.17	Brooks	15.5	0/1	1

* Fusion criteria were defined by 3 categories after 3 months of follow-up: 1) CT-corroborated evidence of osseous fusion, 2) stability on flexion-extension radiographs, and 3) authors' presumption of successful fusion on the basis of plain radiographs.

have not noted any problems with extension of the fusion.[3,17] Extension of the fusion may be a phenomenon associated with older wiring constructs and may not be a common complication of rigid screw instrumentation. Longer follow-up will be required to better ascertain the impact of screw fixation on fusion extension and adjacent-level pathology.

Some of the increased complications associated with the use of wires may also arise from greater halo immobilization in these cases. A larger percentage of patients in the wire cohort were placed in halo immobilization postoperatively, but the majority of patients in both wiring and screw groups had some form of rigid cervical orthosis. Halo-vest placement in young children can carry significant morbidity, but complications are typically minor—such as pin-site infection or pin loosening—and easily managed.[21,30,54] Even with a lower rate of halo immobilization, the patients treated with screw fixation had higher rates of fusion. This may be partially confounded by the increased use of adjuvant agents such as bone morphogenetic protein or demineralized bone matrix. Most of the wiring studies are older and, aside from screws, newer technology alone may confound interpretation of our results.

We also recorded the type and use of bone graft, use of external orthoses, use of biological promoters, and construct subtypes, but the variables were too inconsistently recorded in the published papers to allow useful statistical comparison. In the entire cohort, most patients were treated with autogenous bone graft, and some patients were treated with bone morphogenetic protein or demineralized bone matrix. Earlier studies mostly used autograft from iliac crest, rib, or local bone, whereas recent studies have increasingly shifted toward greater use of synthetic materials such as calcium triphosphate.

With respect to spinal fusion, autograft bone is the gold standard by which all other grafting materials are

Fig. 3. Lateral radiograph of C-1 lateral mass screws with C-2 translaminar screws.

Fig. 4. Lateral radiograph showing wiring (Brooks technique) of the atlantoaxial segments.

judged. Its dependable rate of incorporation leading to a successful spinal arthrodesis has been documented. Cadaveric allograft has been widely used as an alternative, but recent research and development have led to various synthetic "allograft" materials that provide a scaffold for bone growth based on combinations of calcium, phosphate, collagen and/or hydroxyapatite. The potential benefits of using recombinant human bone morphogenetic protein–2 (rhBMP-2) over autograft or allograft bone are numerous. These may include decreased operative time, blood loss, donor-site morbidity, transmission of infection associated with use of allograft, and rate of pseudarthrosis. In addition, its unlimited quantity and immediate availability make it useful in certain pediatric spine applications, although its cost may be prohibitive in some settings. There are concerns regarding the routine and "off-label" substitution or supplementation of autologous or allograft bone graft with rhBMP-2. The most significant concerns involve the possibility of bony overgrowth, interaction with exposed dura, cancer risk, systemic toxicity, local toxicity, immunogenicity, osteoclast activation, and effects on distal organs.[24]

Use of alternate bone scaffolds (osteoconduction) in conjunction with adjuvant bone marrow aspiration or biological agents that contain precursor cells to promote osteogenesis, and in some cases osteoinduction, provides the required elements for osseous fusion. Limited studies are available comparing differing products to distinguish clinical superiority, leaving selection of graft material largely to the discretion of the surgeon.

Fig. 5. Lateral radiograph highlighting C-1 lateral mass fixation with C-2 pars screws and C3–6 lateral mass fixation.

TABLE 4: Complications associated with cervical spine fusions not involving the occipitocervical junction*

Authors & Year	No. of Pts	Sex Ratio (F/M)	Mean Age (yrs)	FU (mos)	Complications	No. of Compls	No. of Pts w/ Compls	No. of Pts w/ Mult Compls
Brockmeyer et al., 1995	8	5:03	11.8	14.5	superficial wound infection	1	1	0
Wang et al., 1999	13	4:09	9.5	26.2	ext of fusion, graft donor-site pain	5	5	0
Sasaki et al., 2000	1	0:01	5	12	wound infection	1	1	0
Meyer et al., 2001	3	1:02	13	17.3	none	0	0	0
Beiner et al., 2006	1	1:00	10	36	kyphotic deformity	1	1	0
Leonard & Wright, 2006	2	0:02	16	12	none	0	0	0
Haque et al., 2009	13	NA	9.7	14.6	none	0	0	0
Heuer et al., 2009	6	4:02	12.7	14.7	trans paresthesias	2	2	0
Desai et al., 2010	8	6:02	9	23	none	0	0	0
Ni et al., 2010	5	1:04	10	14.4	none	0	0	0
Plant et al., 2010	1	0:01	10	36	pseudarthrosis; rod migration	2	1	1
present paper	10	6:04	9.1	11.6	none	0	0	0
(The articles listed in the upper part of the table represent primary screw constructs; the lower part, primary wiring techniques.)								
Roy & Gibson, 1970	5	NA	11.4	NA	pseudarthrosis, infection, graft harvest–site pain	4	3	1
McWhorter et al., 1976	6	3:03	5.9	85.2	graft displacement w/ reop	1	1	0
Segal et al., 1991	4	2:02	6.7	17	death, respiratory arrest, cerebral infarcts, graft resorption, adj-level instability	5	4	1
Smith et al., 1991	17	NA	NA	25	death, quadriparesis, pseudarthroses, trans radiculopathy, neurol impairment, graft donor-site pain, atelectasis	6	9	2
McGrory & Klassen, 1994	42	14:28	12.7	210	unintended fusion ext, iliac graft–site pain, wrong level, pseudarthroses, superficial infection, adj-level instability	28	26	0
Lowry et al., 1997	22	10:11	9.8	12.9	pseudarthroses, graft resorption, infection, adj-level hypermobility	13	8	3
Heilman et al., 2001	1	0:01	4.1	36	CSF leak requiring lumbar drain	1	1	0
Stevenson et al., 2002	1	0:01	15	38	wire migration, osteomyelitis, cerebellar abscess	1	1	0
Pahys et al., 2008	1	1:00	8	2	seroma requiring reop	1	1	0
Visocchi et al., 2009	1	0:01	12	46	none	0	0	0
present paper	1	0:01	0.2	15.5	pseudarthrosis	1	1	0

* Adj = adjacent.

Furthermore, our review is drawn from retrospective series and is therefore subject to the inherent limitations of such studies. Many series found in the literature report data for a heterogeneous group of patients; thus, we were only able to divide the patients into very broad categories and had to exclude several studies. Inconsistent reporting of specific variables that undoubtedly impact outcomes also limits significant interpretation of our review. Moreover, some authors may have published the same clinical outcomes in differing series, which could possibly lead to data repetition. We were unable to identify which cases may have been duplicated; therefore, some results may be skewed based on these studies.

Conclusions

As pediatric fusion constructs have evolved from in situ fusions to rigid internal fixation, better fusion rates—without the need for prolonged, bulky, and, at times, dangerous external immobilization—have been achieved. Although the available data regarding complications are limited, this review of the literature supports the assertion that the complication rates associated with rigid internal screw instrumentation are lower than those associated with older wiring constructs.

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: Jea. Acquisition of data: Jea. Analysis and interpretation of data: Jea. Drafting the article: Jea, Hwang, Gressot. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Jea. Administrative/technical/material support: Jea. Study supervision: Jea.

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