Surgical Technique: Vertebral Column Resection (VCR) for Severe Pediatric and Adult Spinal Deformity

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Study Design: Prospective, clinical series.

Objective: To examine the indications, correction rates, and complications of a posterior vertebral column resection (VCR) approach for severe pediatric and adult spinal deformity.

Summary of Background Data: The ability to treat severe pediatric and adult spinal deformity through an all-posterior VCR approach has obviated the need for a circumferential anterior and separate posterior approach in both primary and revision settings. To date, no North American clinical series involving primarily thoracic-based deformities has been published on this technique

Methods: Between 2002 and 2006, 43 consecutive patients underwent a posterior-only VCR for severe scoliosis (S) (n=7, mean 85.3°, range 45-150°); global kyphosis (GK) (n=12, mean +92.5°, range 70-+118°); angular kyphosis (AK) (n=10, mean +72.7°, range 44-+135°); or kyphoscoliosis (K+S) (n=14, mean total K+S 193.7°, range 149-275°)

by a single surgeon. There were 31 pediatric (ave. age 13), and 12 adult (ave. age 52) patients with 19 primary and 24 revision cases. All patients underwent a 1-level (n=25), 2-level (n=15), or 3-level (n=5) VCR utilizing pedicle screws, anteriorly positioned cages (n=31), and intraoperative spinal cord monitoring. 40 out of 43 (93%) were performed at L1 or cephalad in spinal cord (SC) territory; the remainder were in the upper cauda equina (L2 and/or L3).

Results: The major curve correction was 73° (69%) for the S cases, 44° (54%) for the GK cases, 48° (63%) for the AK cases, and a combined 110° (55%) for the K+S cases. 7 patients (18%) lost intraoperative NMEP data during correction with data returning to baseline following prompt surgical intervention. All patients following surgery were at their baseline (n=40) or showed improved SC function (n=3), while no one worsened. 2 patients had nerve root palsies postop (unilateral quad deficit in a revision L2 & L3 VCR, unilateral foot drop in a revision T12 & L1 VCR with preop 4/5 strength) resolving spontaneously 6 months/2 weeks respectively. No patient thus far has required revision surgery for any neurologic, wound, instrumentation, or fusion complication.

Conclusion: A posterior-based VCR is a safe but challenging technique to treat severe primary or revision spinal deformities with no spinal cord-related, wound, instrumentation, or fusion complications thus far. Intraoperative SCM (especially motor-evoked potentials) is mandatory to prevent spinal cord-related neurologic complications.

Précis: The ability to treat severe pediatric and adult spinal deformity through an all-posterior VCR approach has obviated the need for a circumferential approach in primary and revision settings. This is the largest North American series to date of a posterior-based VCR procedure for severe pediatric and adult spinal deformity. Intraoperative use of spinal cord monitoring, (specifically NMEP) is mandatory to prevent neurologic complications. Although technically challenging, a single stage approach offers dramatic correction in both primary and revision surgery of severe spinal deformities.

Key Points:

1. The ability to treat severe pediatric and adult spinal deformity through an all-posterior VCR approach has obviated the need for a circumferential approach in primary and revision settings.

2. Acceptable spinal deformity correction can be obtained through this all-posterior approach, similar if not superior to patients treated with a circumferential and anterior and separate posterior approach.

3. The use of spinal cord monitoring, especially some type of motor tract monitoring is imperative to maintain neurologic function during these challenging procedures.

Introduction

The surgical treatment of severe spinal deformity has traditionally been based on a circumferential approach to the spinal column. (16,17,20) In a first stage anterior approach, multilevel discectomies and/or corpectomies are performed for release of the rigid spinal column. In addition, anterior spinal fusion is obtained through grafting of the released disc spaces, and/or placement of morselized vertebral body bone back into any corpectomy defects that were performed in anticipation of a circumferential vertebrectomy procedure. Then, either on a same-day or staged basis, a posterior procedure is performed for instrumentation, correction, and ultimate fusion. Concomitant with the posterior approach, posterior releases of the ligaments and facet joints (Ponte or Smith-Petersen type osteotomies) are performed versus a posterior laminectomy and pediclectomy for completion of a circumferential vertebral column resection (VCR) approach. This approach has been the standard of care of severe, rigid spinal deformities for several decades once segmental spinal instrumentation made stable instrumentation constructs possible for the treatment of these severe deformities.

Performing a circumferential VCR approach for severe, rigid spinal deformity was first described by Bradford in the late 1980s.(1) He was the first to describe the use of a circumferential vertebral column resection coupled with concave rib osteotomies, convex thoracoplasty, and segmental spinal instrumentation with fusion in 13 patients with severe structural spinal deformities. In 1997, he and O. Boachie-Adjei (2) further expanded on Bradford's original case series by which they reported on 16 patients undergoing a circumferential VCR. Excellent deformity correction and rebalancing of the trunk was reported with few serious complications. More recently, Suk et al reported on a posterior-only approach with a VCR for fixed lumbar spinal deformities (3), as well as for severe, rigid scoliosis. (4,5) They reported excellent surgical correction with minimal long-term complications for lumbar deformities resected around the cauda equina region, with similar results for the thoracic scoliosis patients except for one permanent paraplegia postoperative. To date, no North American clinical series has reported on this technique for the treatment of primarily thoracic-based, severe pediatric and adult spinal deformities.

The purpose of this study was to examine the indications, correction rates, perioperative and postoperative morbidity and complications of an all-posterior VCR approach for the treatment of severe pediatric and adult spinal deformity by a single surgeon. This posterior VCR approach has obviated the need for a circumferential approach in both primary and revision settings for all patients with severe spinal deformities since 2002.

Material and Methods

Between 2002 and 2006, 43 consecutive pediatric and adult severe spinal deformity patients underwent a posterior-only vertebral column resection (VCR) performed by a single surgeon. Indications for surgery were severe and/or rigid spinal deformity divided into four categories: 1) scoliosis (n=7, mean 85°, range 45-150°); 2) global kyphosis (n=12, mean +92°, range 70 to +120°); 3) angular kyphosis (n=10, mean +72°, range 43 to +135°); and 4) combined kyphoscoliosis (n=14, mean total kyphosis + scoliosis 193°, range 149-275°). The diagnoses for the scoliosis patients included idiopathic-4, neuromuscular-1, and congenital-2. The diagnoses for the global kyphosis patients included Scheuermann's-3, congenital-3, and neuromuscular-2, arthrogryposis-1, post-vertebroplasty collapse-1, post-traumatic-1, Klippel-Feil-1. The diagnoses for the angular kyphosis patients included neurofibromatosis-2, congenital dislocations of the spine-2, congenital kyphosis-2, neuromuscular-2, post-laminectomy kyphosis-1, and post-radiation-1. Lastly, the diagnoses for the kyphoscoliosis patients included idiopathic-7, neuromuscular-3, congenital-2, and neurofibromatosis-2.

There were 31 pediatric patients (average age 13, range 4-18 years) and 12 adult patients (average age 52, range 20-73). Patients underwent a one-level (n=25), two-level (n=13), or three-level (n=5) posterior VCR. The majority of the procedures (40 out of 43, 90%) were performed at the L1 or cephalad region of the spinal cord. The remaining three procedures were performed in the upper cauda equina region (L2 and/or L3). Table 1 includes specific demographic details on all patients, while table 2 includes corresponding radiographic data.

Table 1 - Demographic Data on 43 Patients

Pt. #	**Age (yrs.)**	**Sex**	**Dx.**	**Prior Surgery (Y/N)**	**Vertebrra Resected**	**Single or 2 Stage**	**OR Time**	**EBL (mL)**	**F/U (mos.)**
12	10	M	SS	N	L1	1	590	500	14
17	10	F	SS	N	T12, L1 HV	1	490	500	6
28	59	F	SS	N	T9	1	541	1500	6
33	16	F	SS	Y	T9	1	457	500	4
34	10	M	SS	N	T12	1	615	650	6
36	6	M	SS	N	T3	1	400	550	6
40	18	M	SS	N	T9	2	1100	3100	6
Ave. Range	***18.4 yres. 6-59***	***3F/4M***					***599 mins. 400-1100***	***1042.9 mL 500-3100***	***6.9 mos. 4-14***
Pt. #	**Age**	**Sex**	**Dx.**	**Prior Surgery**	**Vertebrra**	**Single or 2**	**OR**	**EBL**	**F/U**

	(yrs.)			(Y/N)	Resected	Stage	Time	(mL)	(mos.)
10	18	F	GK	N	T10	2	355	500	13
15	13	M	GK	Y	C6,C7	1	480	750	8
21	15	M	GK	Y	T12,L1	Tissue exp. for gibbous deformity then OR	630	600	14
23	73	M	GK	N - Vertebroplasty	T9,T10	1	795	3000	12
24	47	F	GK	Y	L1	1	657	2500	13
26	13	F	GK	N	T7	1	364	750	12
27	20	F	GK	N	T6	1	405	800	12
29	5	F	GK	Y	T4,T5,T6	1	379	500	12
37	14	M	GK	Y	T6,T7	1	291	375	6
39	46	M	GK	N	T7	2	660	2500	6
41	20	M	GK	Y	T6	1	462	1000	6
42	27	F	GK	Y	T6	1	670	650	6
Ave. Range	***25.9 yrs. 5-73***	***6F/6M***					***512.3 mins. 291-795***	***1160.4 mL 375-3000***	***10 mos. 6-14***

Pt. #	Age (yrs.)	Sex	Dx.	Prior Surgery (Y/N)	Vertebrra Resected	Single or 2 Stage	OR Time	EBL (mL)	F/U (mos.)
3	23	F	AK	Y - Neuroblastoma resection	L1	1	477	500	24
4	6	F	AK	N	L2	1	333	250	12

5	11	F	AK	N	T12	1	325	300	24
6	4	F	AK	N	L2	2	540	1000	30
7	14	M	AK	Y	T3 & T4	1	694	800	33
9	6	M	AK	Y	T3 & T4	1	559	500	33
11	11	M	AK	Y	T11,T12,L1	1	486	1000	12
13	13	F	AK	Y	L2,L3	1	652	1000	11
18	14	M	AK	N	T10	1	407	800	10
43	8	M	AK	Y	L1,L2	1	547	750	5
Ave. Range	***11.0 yrs. 4-23***	***5F/5M***					***502 mins. 325-694***	***690 mL 250-1000***	***19.4 mos. 5-33***

Pt. #	Age (yrs.)	Sex	Dx.	Prior Surgery (Y/N)	Vertebrra Resected	Single or 2 Stage	OR Time	EBL (mL)	F/U (mos.)
1	18	F	KS	Y	T9	1	822	1000	20
2	15	M	KS	N	T12-L2	1	595	1000	7
8	14	F	KS	Y	T8	1	561	500	24
14	20	M	KS	Y	T8,T9,T10	1	796	2500	9
16	15	F	KS	Y	T5	1	541	800	12
19	58	F	KS	N	T10	1	644	1200	12
20	60	F	KS	Y	L1	1	722	3000	12
22	8	M	KS	Y	T11	1	486	750	14
25	16	F	KS	Y	T10,T11	1	605	1250	7
30	11	F	KS	Y	T9,T10	1	493	800	6

31	54	F	KS	N	L1	2	955	2000	6
32	17	M	KS	Y	T9,T10	1	658	2200	6
35	10	M	KS	Y	T7,T8,T9	1	685	1000	6
38	18	F	KS	N	T10,T11	1	540	800	3
Ave. Range	***23.9 yrs. 8-60***	***9F/5M***					***650.2 mins. 486-822***	***1342.9 mL 500-3000***	***10.3 mos. 3-24***

Dx. - diagnosis; EBL - estimated blood loss; F/U - follow-up; SS - severe scoliosis; GK - global kyphosis; AK - angular kyphosis; KS - kyphoscoliosis; HV - hemivertebra

Table 2 - Radiographic Data

Pt. #	**Dx.**	**Preop AP Cobb**	**Preop Coronal Flexibility (degrees/%)**	**Initial PO Coronal Cobb**	**Latest PO Coronal Cobb**	**% Coronal Correction**	**Preop Max Lat. Cobb**	**Preop HE Lat.**	**Initial PO Lat. Cobb**	**Latest PO Lat. Cobb**	**% Sagittal Correction**
12	SS	79°	66°/16%	31°	34°	57%	91°	58°	34°	36°	60%
17	SS	112°	80°/29%	21°	18°	84%	31°	N/A	26°	28°	10%
28	SS	78°	64°/20%	20°	n/a	74%	54°	N/A	24°	N/A	56%
33	SS	78°	76°/3%	40°	39°	50%	25°	N/A	11°	9°	64%
34	SS	45°	42°/7%	15°	14°	69%	12°	N/A	14°	23°	92%
36	SS	53°	50°/6%	3°	3°	94%	29°	N/A	16°	16°	45%
40	SS	150°	140°/6%	42°	68°	55%	40°	N/A	33°	32°	20%
Ave. Range		***85.3° 45-150°***	***74.7°/11.7% 42-150°/3-24%***	***24.6° 3-42°***	***28° 3-68°***	***69.1% 50-94%***					
Pt. #	**Dx.**	**Preop AP Cobb**	**Preop Coronal Flexibility**	**Initial PO Coronal**	**Latest PO Coronal**	**% Coronal Correction**	**Preop Max Lat.**	**Preop HE Lat.**	**Initial PO Lat.**	**Latest PO Lat.**	**% Sagittal Correction**

			(degrees/%)	Cobb	Cobb		Cobb		Cobb	Cobb	
10	GK	11°	N/A	5°	3°	N/A	105°	98°	48°	46°	56%
15	GK	40°	UTD	25°	24°	40%	113°	75°	66°	63°	44%
21	GK	N/A	N/A	N/A	N/A	N/A	113°	91°	43°	46°	59%
23	GK	N/A	N/A	N/A	N/A	N/A	120°	93°	66°	59°	51%
24	GK	N/A	**N/A**	7°	6°	N/A	70°	53°	13°	12°	83%
26	GK	45°	36°/20%	N/A	N/A	87%	94°	81°	40°	39°	59%
27	GK	N/A	N/A	N/A	N/A	N/A	108°	None	46°	48°	56%
29	GK	57°	**N/A**	N/A	N/A	63%	118°	None	61°	84°	29%
37	GK	50°	40°/20%	N/A	N/A	30%	95°	90°	21°	21°	78%
39	GK	N/A	N/A	N/A	N/A	N/A	97°	70°	56°	58°	40%
41	GK	44°	26°/41%	31°	31°	30%	82°	50°	41°	41°	50%
42	GK	N/A	N/A	N/A	N/A	N/A	97°	None	52°	52°	46%
Ave. Range		***41.1° 11-57°***	***34°/27% 26-40°/20-41%***	***17° 5-31°***	***20° 6-35°***	***50% 30-87%***	***92.5° 70-118°***	***77.9° 50-98°***	***46.1° 13-66°***	***48.3° 12-84°***	***54.3% 29-83%***
Pt. #	**Dx.**	**Preop AP Cobb**	**Preop Coronal Flexibility (degrees/%)**	**Initial PO Coronal Cobb**	**Latest PO Coronal Cobb**	**% Coronal Correction**	**Preop Max Lat. Cobb**	**Preop HE Lat.**	**Initial PO Lat. Cobb**	**Latest PO Lat. Cobb**	**% Sagittal Correction**
3	AK	N/A	N/A	N/A	N/A	N/A	44°	15°	7°	5°	87%
4	AK	N/A	N/A	N/A	N/A	N/A	62°	50°	13°	27°	56%
5	AK	23°	15°/35%	8°	5°	78%	45°	None	21°	26°	42%
6	AK	N/A	N/A	N/A	N/A	N/A	52°	26°	14°	15°	71%
7	AK	122°	N/A	22°	18°	85%	135°	None	46°	41°	70%

9	AK	N/A	N/A	N/A	N/A	N/A	80°	None	29°	29°	48%
11	AK	N/A	N/A	N/A	N/A	N/A	92°	83°	45°	28°	70%
13	AK	N/A	N/A	N/A	N/A	N/A	66°	None	None	45°	32%
18	AK	20°	None	6°	10°	50%	56°	44°	18°	18°	68%
43	AK	27°	11°/59%	8°	11°	59%	95°	60°	12°	10°	89%
Ave. Range		***48° 20-122°***	***13°/47% 11-15°/35-59%***	***11° 6-22°***	***11° 5-18°***	***68% 50-85%***	***72.7° 44-135°***	***46.3° 15-83°***	***22.9° 7-46°***	***24.4° 5-45°***	***63.3% 32-89%***

Pt. #	**Dx.**	**Preop AP Cobb**	**Preop Coronal Flexibility (degrees/%)**	**Initial PO Coronal Cobb**	**Latest PO Coronal Cobb**	**% Coronal Correction**	**Preop Max Lat. Cobb**	**Preop HE Lat.**	**Initial PO Lat. Cobb**	**Latest PO Lat. Cobb**	**% Sagittal Correction**
1	KS	54°	46°/15% (36 PP)	22°	26°	56%	60°	68°	29°	37°	38%
2	KS	86°	64°/26%	N/A	30°	65%	107°	79°	None	56°	48%
8	KS	71°	55°/23% (PP)	21°	27°	62%	76°	52°	28°	30°	61%
14	KS	124°	110°/11%	76°	62°	50%	144°	115°	73°	65°	55%
16	KS	68°	62°/9%	41°	35°	44%	138°	103°	86°	80°	42%
19	KS	98°	76°/23%	41°	38°	61%	109°	68°	33°	38°	65%
20	KS	74°	78°/14%	37°	44°	41%	88°	65°	38°	30°	66%
22	KS	127°	88°/31%	76°	52°	56%	110°	85°	67°	55°	50%
25	KS	104°	97°/7%	75°	70°	33%	91°	77°	35°	35°	62%
30	KS	56°	None	28°	28°	50%	83°	None	42°	42°	49%
31	KS	85°	77°/9%	39°	37°	56%	110°	40°	27°	28°	75%
32	KS	91°	77°/15%	20°	11°	88%	109°	75°	67°	71°	35%

35	KS	92°	N/A	57°	58°	37%	87°	None	37°	39°	55%
38	KS	135	121°/10%	39°	41°	70%	140°	None	24°	27°	80%
Ave. Range		***90.1° 52-135°***		***44.4° 20-76°***	***40.2° 11-70°***	***55.1% 33-88%***	***103.6° 60-144°***	***75.2° 40-115°***	***45.1° 28-86°***	***45.2° 27-80°***	***55.8% 35-80%***

AP - anteroposterior; PO - postoperative; HE - hyperextension; PP - push prone

Surgical Technique
The surgical technique involved in a posterior vertebral column resection (VCR) is quite demanding and requires the operating team to be well versed in spinal deformity surgical techniques. The first important component to a successful operation is appropriate patient positioning on the operating frame. We utilize the OSI "Jackson" operative frame, either the open frame with adjustable pads, or for very small patients, the closed frame utilizing chest rolls. All patients receiving preoperative halo-gravity traction (n=27) are positioned with their halo in a lessened amount of traction weight. There were no patients who had counter-traction performed with femoral traction pins so as to avoid over-distraction of the spinal cord since this is a spinal column shortening procedure. Optimal positioning is important during these lengthy procedures in order to avoid excessive pressure points in the axilla and to maintain stability of the trunk. The use of spinal cord monitoring, including some form of motor tract monitoring is strongly recommended.

A thorough subperiosteal dissection of the exposed posterior vertebral column is required. In revision patients, a preoperative 3D CT scan is helpful to understand posterior vertebral column pathoanatomy prior to surgery, and also to confirm expected pathoanatomy intraoperatively as portrayed by the CT scan. Because of the length of these surgeries and the potential for significant bleeding, it is imperative to minimize epidural and osseous blood loss during these surgeries. This is performed not only with careful subperiosteal stripping of the posterior vertebral elements, but also with the use of adjunctive antifibrinolytics such as Aprotinin (Trasylol) or with Tranexamic Acid. Aprotinin was utilized in all pediatric patients (n=31) during their procedure. While the use in adults was initially performed, it is no longer administered due to the risk of renal failure as recently documented in cardiac literature.(6)

Following exposure, posterior column ligament and facet releases/osteotomies (Ponte type osteotomies in previously unfused spines and Smith-Petersen osteotomies in previously fused regions) may be performed. These often are performed at the apex of scoliosis or kyphoscoliosis deformities to also aid in apical pedicle screw fixation. Secure pedicle screw fixation is then obtained for the appropriate levels which are to be included in the definitive instrumentation and fusion. The use of multiaxial reduction screws (MARS) is quite helpful at strategic positions: 1) the apical concave regions of severe scoliosis, 2) the proximal and/or distal regions of severe kyphosis or kyphoscoliosis, 3) the concave lumbar region of any type of deformity in the lumbar spine. Pedicle fixation will provide stability to the spinal column above and below the resection area which is imperative in preventing and/or treating spinal subluxation which is a real risk with these procedures. All pedicle screws in this series were placed using the free hand technique espoused by Kim and Lenke, et al (7) using anatomic landmarks and a special blunt, curved gearshift. The pedicles were palpated to confirm intraosseous borders, under-tapped by 1 mm, repalpated again to confirm intraosseous borders, and then screws were placed.

In the thoracic spine, 5 to 6 cm of the medial rib associated with the level to be resected is removed. Subperiosteal dissection of the medial aspect of the rib is performed. It is cut approximately 5 to 6 cm lateral to the vertebral attachment and then as much of the rib as possible is removed down to the head anteriorly and is kept intact for later placement on top of the laminectomy defect. This is performed prior to the laminectomy to avoid canal intrusion. In primary procedures, super-periosteal dissection around the lateral aspect of the pedicles and vertebral body is performed using Penfield elevators. The soft tissues and the anterior vasculature are held from harms way with either mailable retractors or special lateral wall vertebral body elevators (PSO tool set®, Medtronic Spinal and Biologics, Memphis, TN). In revision cases, a subperiosteal dissection will be required due to previous scarring, with a similar approach to gain access circumferentially around the vertebra(e) to be resected. In both circumstances, the segmental vessels are kept lateral in a soft tissue cuff and should not be violated.

Next, a wide laminectomy is performed centrally over the apical level(s) which are to be resected. Typically, the entire lamina of the level to be resected, the lamina cephalad to the pedicles above, and caudad to the pedicles below, is removed. Normally, for a one-level resection procedure, a posterior column laminectomy will result in a 5 to 6 centimeter exposure of the dura and neural elements. It is important not to minimize the posterior column exposure to gain thorough access to the spinal cord and/or cauda equina circumferential to aid in the resection procedure and also for visualizing any dural impingement during the correction.

Next, the pedicles to be resected are encircled, and removal of the vertebral body is started. Prior to removing the anterior body, a temporary, stabilizing rod should be placed and attached to at least two or three pedicle screws both above and below the resection area. Classically, a unilateral rod is used, however, in severe angular kyphotic or kyphoscoliotic deformities, bilateral rods are recommended to prevent spinal subluxation. The vertebral body resection begins by gaining access to the cancellous bone of the vertebral body through a lateral pedicle-body entrance. Next, curetting of the cancellous bone of the body is performed saving the bone for later bone graft. We have noted that bleeding occurring with a vertebral corpectomy is significantly less in the thoracic spine then when performing similar procedures in the lumbar spine. For a scoliosis or kyphoscoliosis deformity, resecting the apical concave pedicle can be quite challenging since it is very cortical, and in a pure scoliosis deformity, the entire spinal cord/dural sac is resting on the medial concave pedicle which does not have any ventral vertebral body associated with it since the body is swung lateral and dorsal in its rotated position on the convexity. In this regard, using a small, high-speed burr (we prefer the Midas Rex® AM8 [Medtronic, Fort Worth, TX]) is helpful to carefully burr away the cortical bone along this concave region. Thus, in scoliosis and kyphoscoliosis deformities, the majority of the vertebral body will be removed from the convexity of the deformity since that is where the vertebral body is located. We prefer to perform the concave resection of the pedicle prior to the convex removal so there is no bleeding into this dependent concave region. This also allows the concave spinal cord to drift somewhat more medial and remove tension prior to going to the convexity for completion of the corpectomy. The entire body is removed except for the anterior shell, as we like to keep a thin rim of bone intact on the anterior longitudinal ligament (ALL) for fusion purposes. However, if this bone is cortical then it must be thinned to allow easy closure of the resection area.

Next, discectomies both above and below are performed using curettes as needed. It is important not to violate the endplates of the superior and inferoadjacent regions as placement of a structural intracorporeal cage may be required. The last part of the vertebral resection will be the posterior vertebral body wall or floor of the spinal canal. Here it will be essential to control epidural bleeding with the judicious use of bipolar cauterization, topical hemostatic agents such as FloSeal® (Baxter U.S., Deerfield, IL), Gelfoam® (Pharmacia, Kalamazoo, MI), and cottonoids. The dural sac must be circumferentially freed and exposed and then separated from the epidural venous complex as well as the posterior longitudinal ligament (PLL). This posterior vertebral wall must be removed in its entirety with reverse-angled curettes, Woodson elevators, or a specialized posterior wall impactor (PSO tool set®, Medtronic Spinal and Biologics, Memphis, TN) which are utilized to impale the posterior wall into the ventral defect that has been created. It is imperative that the ventral spinal cord is completely free of any bony prominences to avoid impingement during closure. This is especially true at the disc levels, especially above but also below, as there tends to be osteophytic lipping in that region which can cause ventral compression if not removed.

At this point, the resection is complete and closure of the resected area with compression forces is performed. The spinal column is always shortened, not lengthened, with convex compression performed as the main correcting technique. This is performed either with individual pedicle screws in primary cases where a good bony grip of the vertebrae is found, or in a construct-to-construct closure mechanism utilizing dominoes at the apex of the resected area. In this method, closing from a construct rod above to a construct rod below to distribute the forces of correction over several levels is performed. It is imperative to compress slowly as subluxation and/or dural impingement can occur along the way. In any deformity that has a degree of kyphosis (GK, AK, and K+S), we place an anteriorly based structural cage to prevent over-shortening of the deformity, and it also acts as a hinge to provide further kyphosis correction. Typically, the spinal column will be shortened by 1 to 1.5 cm, an appropriate height and length cage will be inserted, and then further closure onto the cage to make it snug and fixed will be performed as a final correction maneuver. Once closure has been fully performed, a permanent contralateral rod is placed with appropriate correction maneuvers performed. Then the temporary closing rod is removed and a permanent, final rod is placed on the contralateral side as well. Appropriate compression and distraction forces, in situ contouring, and other correction techniques may be performed always being mindful of any resultant affect on the resected area with respect to subluxation or dural impingement. Next, adequate alignment is confirmed by intraoperative radiographs. Decortication and bone grafting follow with copious amounts of local graft obtained from the resection procedure. The laminectomy defect is covered with the previously harvested ribs for the costotransversectomy approach. These ribs are split in half longitudinally with the cancellous surface placed along the entire laminectomy defect from the lamina above to the lamina below. This creates a rib "bridge" of bone to protect the dura as well as to provide a posterior onlay fusion. The rib is held in place with sutures or a crosslink if there is room and no prominence. To confirm the absence of impingement, final implant security is documented as well as a final circumferential check of the exposed dura. The vast majority of these procedures (n=38) were performed in a single stage with the remaining (n=5) treated with a 2-staged procedure.

Postoperative Treatment
All patients were rigidly stabilized to allow upright posture immediately after surgery. Most patients sat and dangled on the side of the bed on postoperative day 1, and were out of bed and to a chair by postoperative day 2. A few pediatric patients having soft bone, or those with cervicothoracic constructs were braced for 3 to 4 months after surgery. None of the adult patients were braced after surgery. (Figure 1)

Figure 1A-C. Patient is a 58+7-year-old female with a long-standing kyphoscoliosis and osteoporosis.

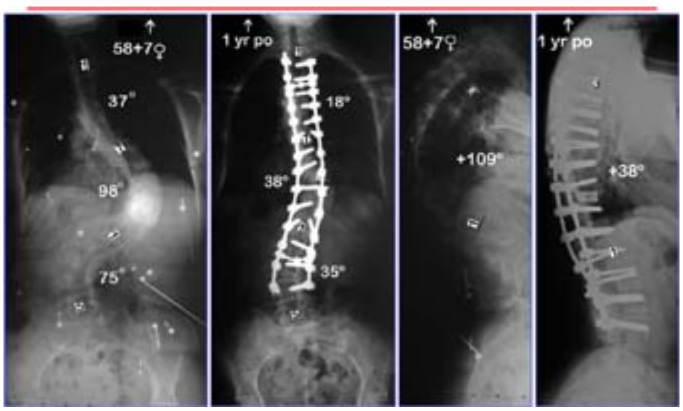


Figure 1A. Her preoperative main thoracic scoliosis measured 98°, side-bending to only 76° (25% flexibility) with a +109° kyphosis hyperextending to +68°.

Figure 1B. She underwent a single-staged posterior T10 vertebral column resection (VCR) with PSF from T2 to L4, and anterior cage placement from T9-T11. Her postoperative coronal correction was at 38° (61%), and her sagittal plane correction was to +38° (67%).

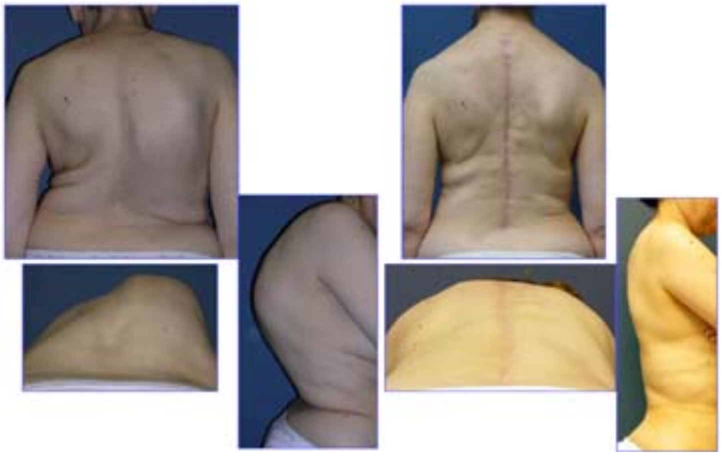


Figure 1C. Her pre and postoperative clinical photographs show the excellent restoration of more normal trunk contours following her single-level VCR without any thoracoplasty procedure performed.

Radiographic

The major curve correction was 73° (69%) for the scoliosis cases, 46° (54%) for the global kyphosis cases, 48° (63%) for the angular kyphosis cases, and a combined 110° (55%) for the kyphosis + scoliosis cases. For the severe scoliosis cases, the mean preoperative coronal Cobb of 85° had a preoperative flexibility of 75° (11%), with initial curve correction averaging 25°, and ultimate correction averaging 28° (69%). For the global kyphosis cases, the preoperative maximum sagittal Cobb of +93° (range 70-+120°) had a preoperative flexibility averaging +78° with initial postoperative correction averaging +46°, and ultimate correction averaging +48° (54%). For the angular kyphosis case, the average preoperative kyphosis of +72° had an average preoperative extension lateral measurement of +46° with initial correction averaging 23°, ultimate correction 24° (63%). Lastly, for the kyphoscoliosis cases, the preoperative mean total kyphosis + scoliosis measurement was 194°, with a combined 103° of initial correction, and 107° of ultimate correction (55%). No patient thus far has required revision surgery for instrumentation, or fusion complications. (Figure 2)

Figure 2A-D. Patient is a 17+8-year-old female with severe idiopathic kyphoscoliosis.

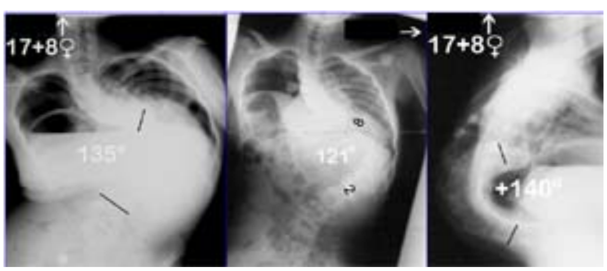


Figure 2A. She had a 135-degree coronal plane deformity bending to only 121° (11% flexibility), and a +140-degree kyphosis deformity. Thus, she had 275° of total kyphoscoliosis deformity.

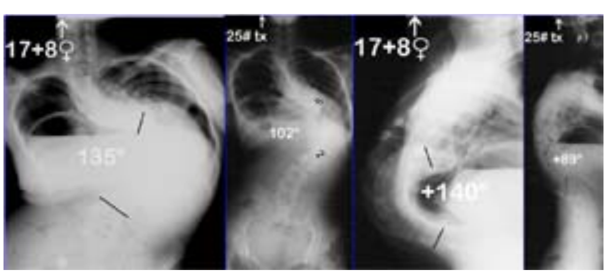


Figure 2B. Preoperatively, she was placed in halo-gravity traction for four weeks to stretch out her spinal column and to improve her nutritional and respiratory statuses. Her ultimate coronal plane deformity corrected to 102° and her sagittal plane to +89°.

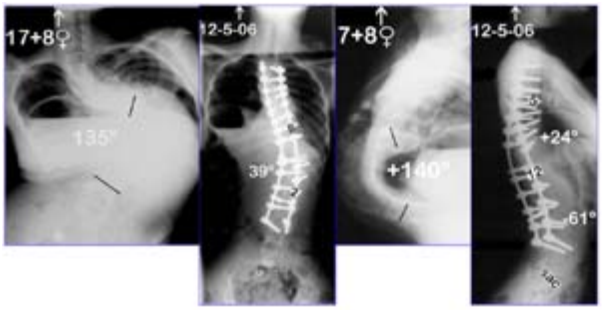


Figure 2C. She underwent a two-stage T10 VCR with PSF from T2 to L4. Her ultimate coronal plane correction was to 39° (72% correction) with sagittal plane correction to +24° (88%).

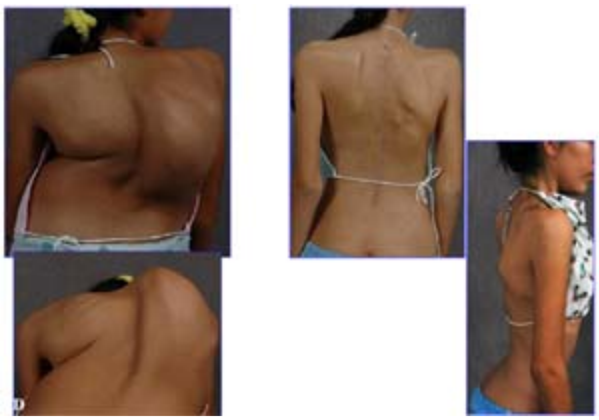


Figure 2D. Pre and postoperative clinic photos show marked correction of her trunk with a concomitant seven-rib thoracoplasty performed in order to gain full access of her posterior spinal column because of her severe deformity.

Table 3: Complications of 43 Patients

Neurologic
Following surgery, all patients were at their baseline (n=40) or showed improved spinal cord function (n=3), while no one worsened. Seven patients (18%) lost intraoperative NMEP data during correction with data returning to baseline following prompt surgical intervention. All seven of these patients had some form of preoperative kyphosis (GK-1, AK-2, and K+S-4). Five of the seven patients had some type of spinal column subluxation occur during the vertebrectomy site closure. In five of the patients, subluxation occurred with actual closure of the vertebrectomy site with the most common impingement being the ventral aspect of the proximal level of the spinal cord. In one patient (GK) NMEP data were lost with closure, and returned with reopening the osteotomy site and closure over a cage. (Figure 3) In another patient (AK), over-shortening of the spinal cord occurred with closure over a small cage. When a larger cage was inserted with compression, the data remained normal. All seven of these patients had NMEP data return to baseline promptly following the surgical correction of subluxation or placement of a larger anterior cage.

Figure 3A-H. Patient is an 18+6-year-old female with a combined Scheuermann's/congenital kyphosis.

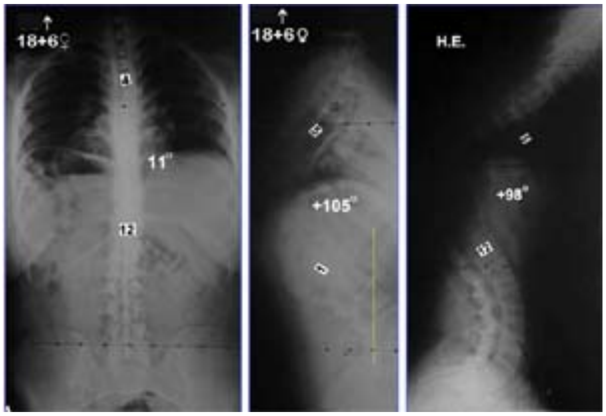


Figure 3A. She had a +105-degree sagittal plane deformity, correcting to only +98° (6%) on hyperextension.

Figure 3B. Her preoperative MRI showed ventral dural compression along the entire posterior edge of her global kyphosis deformity as well as fused posterior apical facet joint. She also exhibited exertional myelopathy. Statically she had normal neurology, but after walking for longer than 15 minutes, her legs became heavy, numb, and she exhibited bilateral clonus and up-going toes.

Figure 3C. Further complicating the matter was her weight at 285 pounds (preop clinical photos).

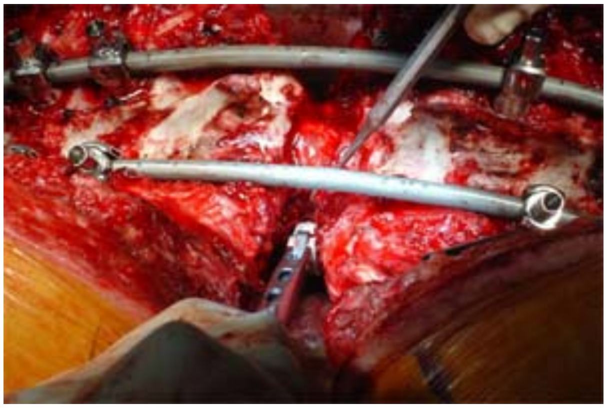
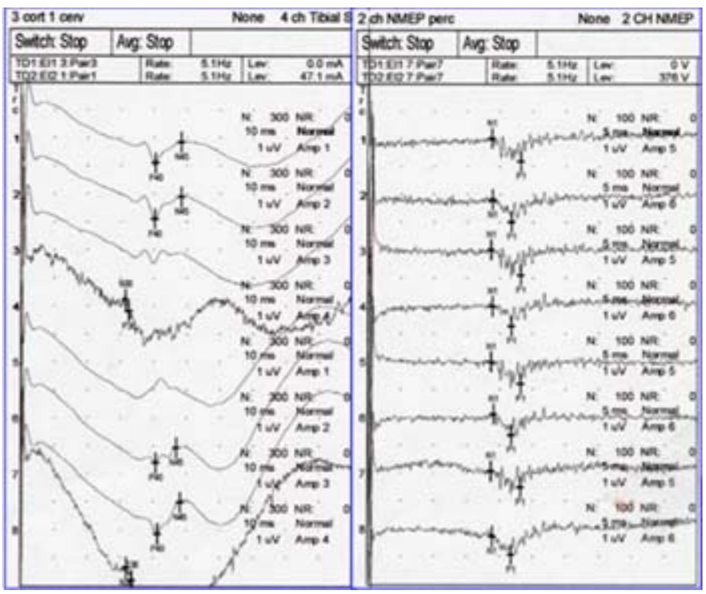
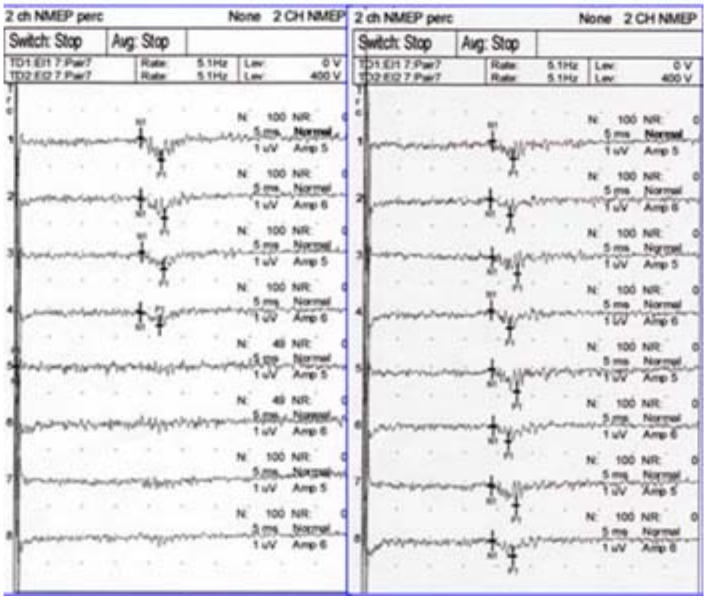


Figure 3D. She underwent a single-level posterior vertebral column resection (VCR) with anterior cage placement, following closure of her deformity over the cage;





Figures 3E. NMEP data was lost bilaterally, with return of data following release of her correction, and placement of a larger cage.

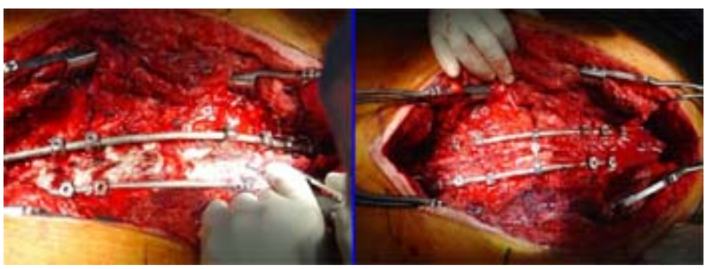


Figure 3F. She eventually had her final construct with intact NMEP data with rib bridge strut grafts placed over the laminectomy defect for the definitive posterior instrumentation and fusion.

Figure 3G. Her one-year postoperative films show correction of her kyphosis to +46° with normal coronal and sagittal radiographic contours.

Figure 3H. Her pre and postoperative clinical photos are demonstrated.

Table 3 - Complications of 43 Patients

Pt. #	Dx.	Intraoperative	Postoperative
12	SS	None	None
17	SS	None	Diarrhea PO day 5, (+) for C-diff; AB given
28	SS	None	None
33	SS	None	None
34	SS	None	None
36	SS	None	None
40	SS	None	None
10	GK	NMEP loss/larger cage placed/ subluxation reduced	None
15	GK	None	Respiratory distress requiring emergency tracheostomy
21	GK	No SCM possible; failed wake-up test/ larger cage placed	Bilateral LE subjective "numbness" - subsided by 1 month PO; 4/5 EHL X 1 week
23	GK	None	(L) pulmonary effusion - resolved

24	GK	None	None
26	GK	None	Pleural effusion - started diuretics - resolved
27	GK	None	None
29	GK	None	None
37	GK	None	None
39	GK	None	Respiratory failure - re-intubation required x2 days
41	GK	None	None
42	GK	None	None
3	AK	None	None
4	AK	None	None
5	AK	None	DVT (R) leg; Leovenox therapy
6	AK	None	None
7	AK	None	None
9	AK	No SCM	None
11	AK	NMEP loss/ larger cage placed	None
13	AK	(L) quad palsy noted on wake-up test; (L) L2-L3 roots re-explored	Decreased strength (L) quad - normal by 6 mos. PO
18	AK	None	None
43	AK	None	None
1	KS	None	None
2	KS	None	None
8	KS	None	Prolonged ileus

14	KS	None	None
16	KS	None	Tongue swelling; small area of necrosis - resolved
19	KS	None	Pleural effusion, no CT needed
20	KS	None	4 days in ICU secondary to low blood pressure, (L) pleural effusion - resolved
22	KS	None	None
25	KS	NMEP loss/ reduced subluxation	Respiratory failure - mechanical vent x4 days
30	KS	None	None
31	KS	None	None
32	KS	None	None
35	KS	NMEP loss/ reduced subluxation	Brachial plexus palsy - resolved by 6 weeks PO
38	KS	NMEP/SSEP loss; failed wake-up test; (R) LE procedure aborted; NL final wake-up test	(L) pleural effusions requiring bilateral chest tube placement

AP - anteroposterior; PO - postoperative; HE - hyperextension; PP - push prone

One patient had loss of unilateral SSEP and NMEP data on the convexity of a large kyphoscoliosis with a failed intraoperative unilateral wake-up test. A temporary rod was placed, the procedure was aborted, and the patient's wound was closed. It was thought that the deficit was most likely due to inadvertent unilateral spinal cord compression from a cottonoid placed to control copious epidural bleeding on the convex side. Following removal of the cottonoid, the SCM data returned to baseline. Following wound closure, the patient awoke with completely normal neurologic function in both lower extremities. She remained neurologically intact and her surgery was completed one week later without neurologic sequelae.

Intraoperative NMEP data was unobtainable in three patients in this series. All three of these patients had prior surgery, while two out of three had prior intradural surgery. One of these patients failed a wake-up test following closure of the vertebrectomy defect. However, function returned following re-opening of the defect, placement of an anterior cage, then recompressing posteriorly.

Two patients had nerve root palsies after surgery. One patient who underwent a revision L2 and L3 VCR had a unilateral quadriceps deficit that was noted immediately after surgery. The patient was returned prone on the operating table where the left-sided L2 and L3 nerve roots were re-explored and further decompression was performed. The deficit resolved spontaneously six months postoperative. A second case, a revision T12 and L1 VCR with preoperative 4/5 strength of the lower extremities had a unilateral foot drop that resolved by two weeks postoperative. No patient thus far has had revision surgery for any neurologic complication. And all patients (n=4) with preoperative spinal cord myelopathy either awoke the same (n=1) or became stronger (n=3) soon after the surgery. (Figure 4)

Figure 4A-D. Patient is a 14+7-year-old male with neurofibromatosis and eight prior anterior and posterior spinal decompression and fusion attempts with a solid C2-T2 fusion mass. He was myelopathic, could stand but barely walk, with grade 3+/4- out of 5 strength in his lower extremities.

Figure 4A. He had a chin-on-chest deformity and a +135-degree cervicothoracic kyphotic deformity.

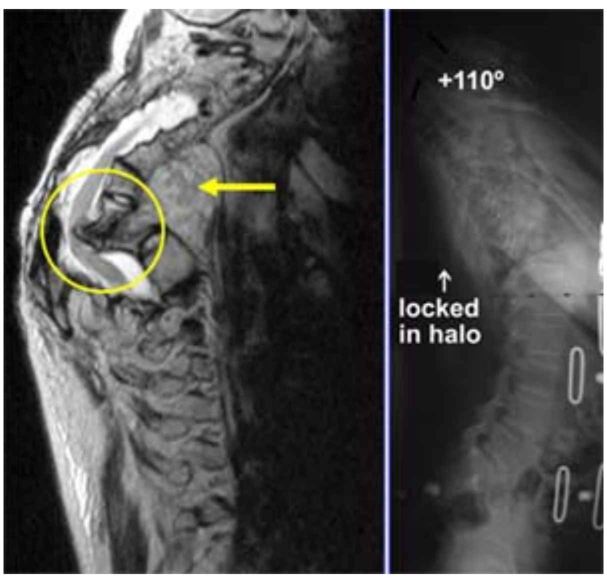


Figure 4B. His preoperative MRI showed a kyphotic T4-5 dislocation with severe compression of the spinal cord at the level. He was initially placed in gradual halo traction which was locked with his chin out of his chest to allow for fiberoptic intubation with access to his neck if required.

Figure 4C. He then underwent a posterior T4 and T5 VCR and an occiput to T11 posterior instrumentation and fusion. 1+6 years postop, he had a stable construct and alignment with marked correction of his kyphosis to +41°.

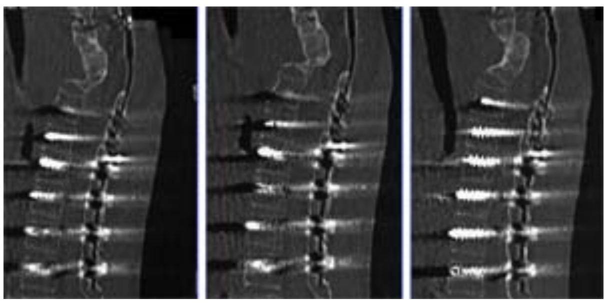


Figure 4D. A one-year postoperative CT scan shows a solid anterior fusion noted with the use of BMP-2 anteriorly. He already had a wide laminectomy defect posteriorly which would not allow for any posterior fusion. His neurologic function improved to normal by 6 weeks postoperative.

Non-neurologic
No patient required a chest tube for a pleural air leak, but a staged patient required bilateral chest tubes for pleural effusions postoperative. All patients required intermittent positive pressure breathing (IPPB) during the early portion of their postoperative hospital course for preventing atelectasis. Several patients required up to three days of postoperative ventilation, and one patient was re-intubated approximately five days postoperative for upper airway breathing difficulties following a cervicothoracic reconstruction. One patient had a DVT two weeks postoperative treated with Lovenox. Another patient had a partial bilateral brachial plexus palsy postoperative that was somewhat predicted by degraded upper somatosensory potentials intraoperatively. He awoke with grade 4/5 strength in his arms and hands which returned to normal within one month postoperative. All patients received perioperative TPN through a central venous line catheter that was placed perioperatively. No patient has had any wound related complications thus far.

Results: **Clinical**
Of the 43 patients, 38 were treated in a single-stage, while 5 were treated in a two-staged fashion. The interval between stages ranged from five to seven days. The average EBL for all patients was 1007 cc, ranging from 375 to 3100 cc. No patient became coagulopathic intraoperatively, and no patient received platelets or fresh frozen plasma. The average operative time was 9 hours 23 minutes, ranging from 4h 52m to13h 40m for all the procedures.

Discussion
The surgical treatment of severe spinal deformity is challenging. Traditionally, a circumferential approach with anterior releases via discectomies, followed by posterior instrumentation and fusion has been the standard of care. The use of a vertebrectomy procedure has been around for quite some time as well, with the first description in 1922 by MacLennan8 who described a posterior apical resection followed by postoperative casting for the treatment of severe scoliosis. Following that, several authors recorded their experiences with vertebrectomies, most commonly for the surgical treatment of congenital scoliosis.(9-17) Then in the modern era of spinal deformity surgery, Bradford (1) was the first to describe the use of a circumferential vertebrectomy on patients with severe structural spinal deformities. His report consisted of 13 patients who underwent a 1 to 7 level (average 3 levels) vertebrectomy. Scoliosis patients had a preoperative curve averaging 117°, correcting to an average 55°. Kyphosis patients had a preoperative curve

averaging 112°, correcting to an average 56°. The average estimated blood loss was 5800 cc, and the average operative time was 10.5 hours for these combined procedures. Bradford and Tribus (18) later reported on 24 patients with rigid coronal decompensation who underwent a circumferential vertebral column resection (VCR). The average preoperative scoliosis was 103° corrected by 52%. Importantly, coronal and sagittal imbalances were corrected to an average of 82% and 87% respectively. However, there was an average operative time of over 12 hours, an average blood loss of 5500 mL, and 31 overall complications.

Suk was the first investigator to promote a posterior-only VCR. He believed that there was a reduction in the total operating time, amount of blood loss through this one-stage posterior-only procedure. In 2005, he presented a series of 16 patients (average age 29 years) who underwent a posterior VCR having a minimum 2-year follow-up.(5) His indication for this procedure was scoliosis of more than 80° with flexibility less than 25%. There was an average of 1.3 vertebrae removed, 15 in the thoracic spine and 6 in the lumbar spine. The mean preoperative scoliosis of 109° was corrected to 46° (59% correction). However, complications were encountered in four patients, including one with complete permanent paralysis. He recommended this as an effective alternative for severe rigid scoliosis but cautioned that it was a highly technical procedure and should only be performed by an experienced surgical team. It is important to note, he did not utilize any form of motor tract monitoring during the surgeries, only SSEP monitoring.

Our current series of 43 consecutive patients undergoing posterior-only VCR for severe pediatric and adult spinal deformity is both complimentary and additive to these prior reports. This is the largest reported series on posterior VCRs thus far, and the first from a North American center. In addition, the indications for the procedure were divided into four main groups: severe scoliosis, global kyphosis, angular kyphosis, and kyphoscoliosis. These patients were either in good balance or out of balance prior to their posterior vertebrectomy procedure. These patients would all have undergone a circumferential anterior and posterior procedure versus a circumferential vertebrectomy instead of their posterior VCR. The severe scoliosis cases had a correction rate of 69%, 54% for the global kyphosis cases, 63% for the angular kyphosis cases, and 55% for the combined kyphoscoliosis cases, which is as good as or better than other correction rates reported in the literature by either circumferential or posterior-only vertebrectomy.

Importantly, there were no spinal cord related neurologic deficits in any of these patients in this series, where 40 of the procedures were performed at L1 or cephalad. We attribute this to several factors including the routine use of NMEP monitoring in those patients who had available spinal cord monitoring potentials (n=40 out of 43). In this regard, seven patients lost NMEP data some time during the surgical procedure, most commonly during the actual spinal shortening and correction. The most common reason for lost NMEP data was spinal subluxation which can occur before, during, or even after the corrective procedure. The spine is rendered extremely unstable during this posterior reconstruction, and thus it is imperative to regain primary stability with a dural sac that is free from compression and not excessively shortened ventrally (during kyphotic reconstructions). In three patients (2 with and 1 without available spinal cord monitoring), over-shortening of the ventral spinal cord led to loss of data in one and a failed wake-up test in the other. Restoring appropriate anterior height via a larger anterior cage restored the NMEP data in two, and neurologic function in the other. We also feel strongly about the importance of maintaining normotensive anesthesia during correction and closure of these deformities. We prefer to have the mean arterial pressure (MAP) at least 75 to 80 mm Hg during this time. Occasionally, this will require the adjunctive use of Dopamine as a low-dose inotrope. Often blood products will be given even if the hematocrit seems adequate, as there is a fair amount of hemo concentration that occurs over the course of these procedures depending on the amount of fluids provided by anesthesia. As one might anticipate, the occurrence of NMEP data loss was in patients with a primary or secondary kyphotic malalignment to the spine, with the highest risk being the angular kyphosis group. We recommend strict and vigilant care in these patients which are at a much higher risk of a neurologic deficit during these procedures as they would be in any type of treatment for their deformity.

There are multiple principles that we have gleaned over the past five years of performing these challenging procedures. First, there appears to be no reason to approach these patients circumferentially. In more severe scoliosis, kyphosis, and kyphoscoliosis deformities, the vertebral body is located posteriorly. In addition, as Suk (3,4,5) has suggested, the main advantage of a posterior-based VCR is simultaneous control of the spinal column and access to the neural elements circumferentially to closely follow the both during correction of the deformity. Thus, there is excellent access to the dural tube circumferentially to confirm absence of any type of impingement due to either subluxation or retained bony/disc material during the corrective procedure. This certainly makes the procedure safer from a neurologic prospective.

From a technical perspective, there are several factors that are extremely important including the use of a wide laminectomy from the outset. We prefer now to perform a laminectomy from the inferior pedicles of the level above the resection, distal to the superior pedicles of the level below the resection. There is always a residual laminectomy defect following closure to allow for egression of the dural sac posteriorly in order to avoid dorsal impingement, and allow access to assess the ventral aspect of the dural sac. Another important factor is that it is absolutely imperative to have stable pedicle screw fixation above and below the resected area to maintain spinal alignment, avoid and/or treat subluxation, and provide for adequate correction and final construct stability. (7,19)

Because of the severe instability produced by this approach, it is imperative to have a temporary rod or rods placed to prevent subluxation prior to going ventral into the anterior column and even sometimes before that. The liberal use of multiaxial reduction screws (MARS) is also very helpful in very strategic instrumentation positions including the concave apex of severe scoliosis, the cephalad or caudal aspect of a kyphotic reconstruction, and immediately caudal to the resected area. Because the lower spine and hips are usually in extension on the operating room table, it is most common that the distal spinal column will tend to migrate ventrally following the resection and during the closure of the vertebrectomy site, which tends to put ventral pressure on the more proximal limb of the neural elements. This can be remedied by using MARS just caudal to the resection area to translate the distal fragments posteriorly to reduce this subluxation.

For the vertebral resection procedure, the use of a high-speed diamond-tipped burr such as the Midas Rex AM8 (Medtronic, Fort Worth, TX), is extremely beneficial. The apical concave pedicles of a scoliosis or kyphoscoliosis, and the ventral vertebral body bone of long-standing angular kyphosis cases are extremely cortical in nature. This bone is very difficult to resect with curettes or rongeurs, and "painting" the bone away with a high-speed burr while protecting the neural elements/dural sleeve with Penfield-type retractors, has proven extremely helpful. In addition, the use of an anterior structural cage is also essential for avoiding ventral spinal cord buckling or excessive shortening which occurs during closure especially in a kyphotic malalignment. This also allows procurement of an anterior arthrodesis from the endplates above and below following the discectomies both above and below the resected area. To cover the laminectomy site and also help procure a posterior arthrodesis, any ribs that are excised during thoracic-level vertebrectomies are bivalved longitudinally and placed cancellous surface ventral over the remaining laminar segments above and below as a "bridge" graft.

Lastly, as evidenced by prior reports, these surgeries have a very high neurologic risk. This is in part due to the severe nature of the deformity, and in part due to the instability created in order to correct these deformities with segmental instrumentation.20 Thus, it is imperative to use intraoperative spinal cord monitoring with some form of motor tract monitoring to provide early detection of data loss, which allows for immediate correction of the causation. In our series, of the 40 cases that had monitoring out of which seven lost data, we were fortunate to have the NMEP data return quickly with the aid of prompt and precise surgical techniques. While difficult to prove, it is certainly realistic that our neurologic complication rate would have been much higher without the early detection that is obtainable with the use of multimodality spinal cord monitoring.

In conclusion, a posterior-based VCR is a safe but challenging technique to treat severe primary or revision pediatric and adult spinal deformity. In this consecutive series of 43 patients, there have been no spinal cord-related, wound, instrumentation and fusion complications thus far. Intraoperative spinal cord monitoring, especially some form of motor tract monitoring, is mandatory to prevent spinal cord-related neurologic complications. This posterior-only approach also allows for dramatic radiographic and clinical correction of these severely deformed patients.