Eur Spine J
DOI 10.1007/s00586-017-5071-1

ORIGINAL ARTICLE

Three-column osteotomy for correction of cervical and cervicothoracic deformities: alignment changes and early complications in a multicenter prospective series of 23 patients

Justin S. Smith[1] · Christopher I. Shaffrey[1] · Renaud Lafage[2] · Virginie Lafage[2] · Frank J. Schwab[2] · Han Jo Kim[2] · Justin K. Scheer[3] · Themistocles Protopsaltis[4] · Peter Passias[4] · Gregory Mundis[5] · Robert Hart[6] · Brian Neuman[7] · Eric Klineberg[8] · Richard Hostin[9] · Shay Bess[4] · Vedat Deviren[10] · Christopher P. Ames[11] · ISSG

Received: 17 November 2016 / Revised: 22 February 2017 / Accepted: 26 March 2017

Abstract

Purpose Three-column osteotomy (3CO), including pedicle subtraction osteotomy (PSO) and vertebral column resection (VCR), can provide powerful alignment correction for adult cervical deformity (ACD). Our objective was to assess alignment changes and early complications associated with 3CO for ACD.

Methods ACD patients treated with 3CO with minimum 90-day follow-up were identified from a prospectively collected multicenter ACD database. Complications within 90-days of surgery and pre- and postoperative radiographs were collected.

Results All 23 ACD patients treated with 3CO (14 PSO/9 VCR) had minimum 90-day follow-up (mean age 62.3 years, previous cervical/cervicothoracic instrumentation in 52.2% and thoracic/thoracolumbar instrumentation in 47.8%). The primary diagnosis was kyphosis in 91.3% and coronal deformity in 8.7%. The mean number of fusion levels was 12 (range 6–18). The most common 3CO levels were T1 (39.1%), T2 (30.4%) and T3 (21.7%). Eighteen (12 major/6 minor) complications affected 13 (56.5%) patients. The most common complications were neurologic deficit (17.4%), wound infection (8.7%), distal junctional kyphosis (DJK 8.7%), and cardiorespiratory failure (8.7%). Three (13.0%) patients required re-operation within 90-days (1 each for nerve root motor deficit, DJK, and implant pain/prominence). Cervical alignment improved significantly following 3CO, including cervical lordosis ($-2.8°$ to $-12.9°$, $p = 0.036$), C2-7 sagittal vertical axis (64.6–42.3 mm, $p < 0.001$), and T1 slope minus cervical lordosis (46.4°–27.0°, $p < 0.001$).

Conclusions Among 23 ACD patients treated with 3CO, cervical alignment improved significantly following surgery. Thirteen (56.5%) patients had at least one complication. The most common complications were neurologic deficit, infection, DJK, and cardiorespiratory failure.

Keywords Adult · Cervical deformity · Kyphosis · Osteotomy · Surgery

✉ Justin S. Smith
jss7f@virginia.edu

[1] Department of Neurosurgery, University of Virginia Health Sciences Center, PO Box 800212, Charlottesville, VA 22908, USA

[2] Department of Orthopaedic Surgery, Hospital for Special Surgery, New York, NY, USA

[3] School of Medicine, University of California San Diego, San Diego, CA, USA

[4] Department of Orthopaedic Surgery, NYU Hospital for Joint Diseases, New York, NY, USA

[5] San Diego Center for Spinal Disorders, La Jolla, CA, USA

[6] Department of Orthopaedic Surgery, Oregon Health and Science University, Portland, OR, USA

[7] Department of Orthopaedic Surgery, Johns Hopkins University, Baltimore, MD, USA

[8] Department of Orthopaedic Surgery, University of California, Davis, Sacramento, CA, USA

[9] Department of Orthopaedic Surgery, Baylor Scoliosis Center, Plano, TX, USA

[10] Department of Orthopedic Surgery, University of California, San Francisco, San Francisco, CA, USA

[11] Department of Neurological Surgery, University of California, San Francisco, San Francisco, CA, USA

Introduction

Although adult cervical deformity (ACD) can have profound impact, including pain, disability, and neurologic compromise, few reports are available that characterize these patients or provide guidance for their treatment [1]. In contrast to the management of throracolumbar deformities for which substantial advances have been made over recent decades [2], the study and treatment of patients with ACD have only more recently gained momentum [1, 3–7].

Correction of spinal deformities often relies upon the use of osteotomies. These have been widely applied for the correction of thoracolumbar deformities and are similarly important for the correction of cervical deformities [1]. A recent report has proposed a standardized nomenclature for the application of osteotomies to correct cervical deformities, ranging from soft tissue and facet release to three-column osteotomies (3CO), which include pedicle subtraction osteotomy (PSO) and vertebral column resection (VCR) [4]. For both thoracolumbar and cervical deformities, 3COs are typically reserved for the most severe and often rigid deformities that cannot be readily corrected with other techniques, since these osteotomies are the most aggressive and tend to be associated with high rates of complications [6, 8, 9].

Early reports on the application of 3CO for treatment of ACD focused on single case reports of severe rigid deformities or on small retrospective case series from a single surgeon or institution [10–12]. These early reports applied techniques that were at the time considered high risk and tended to have high rates of major complications. More recently, reports have described the 3CO techniques and experiences of individual surgeons based on retrospective reviews of patients surgically treated for ACD [5–7, 13–15]. However, few of these reports provide documentation of complications beyond noting major neurological deficits and none provides a detailed assessment of the complications. In addition, the retrospective designs of these previous reviews may result in significant underestimates of the true complication rates [9].

In the present study, we provide assessment of a prospectively collected multicenter series of ACD patients treated with a 3CO for cervical and cervicothoracic deformities. Our objectives were: (1) to assess the baseline characteristics of a patient population treated with 3CO for ACD, including demographics, diagnosis, and radiographic parameters, (2) to summarize surgical parameters associated with 3CO for ACD, including vertebral level of the osteotomy, numbers of levels fused, and the occurrence of early complications (within 90 days of surgery), and (3) to assess the changes in cervical alignment following 3CO. In addition, we provide a case example of a patient who underwent a 3CO for chin-on-chest cervical deformity, including clinical images for which she provided consent for publication.

Methods

Data collection and radiographic assessment

Consecutive adult patients presenting for surgical evaluation of cervical and cervicothoracic deformities were prospectively enrolled at 13 centers across the US as part of an ongoing study to assess clinical and radiographic features of ACD and outcomes following surgical treatment. Institutional review board approval was obtained from each participating site prior to enrollment, and patient consent was obtained for each enrolled patient. Inclusion criteria were: age $\geq$18 years, presence of cervical deformity, and plan for surgical correction of the deformity. For the purposes of this prospective database, cervical deformity was defined as the presence of at least one of the following: cervical kyphosis (C2-7 sagittal Cobb angle $>10°$), cervical scoliosis (C2-7 coronal Cobb angle $>10°$), C2-7 sagittal vertical axis (C2-7 SVA) >4 cm, or chin-brown vertical angle (CBVA) $>25°$ [1]. Patients with active tumor or infection were excluded from the study. The operative approach, procedural choice, and instrumentation were at the discretion of the operating surgeon. Osteotomies were performed as previously described [7, 13].

Standardized collection forms were used to collect patient demographics, clinical data, type of deformity, surgical procedure details, and complications. A complication reporting form was completed perioperatively and at follow-up time intervals. The present study focuses on early complications, specifically those reported from the perioperative period up to 90 days following surgery. During the perioperative period and at follow-up time intervals, patients were assessed for complications based on examination, imaging, and questioning. For the present study, dysphagia was only reported as a complication if clinically significant, since standardized assessments to detect more subtle cases were not routinely performed. Screening for pulmonary embolism and lower extremity deep venous thrombosis was not routinely performed across institutions and, therefore, this study focuses primarily on those that presented clinically. It remains controversial whether "excessive" blood loss without apparent sequelae should be considered a complication in spine surgery. Since blood loss was not clearly associated with the occurrence of any complications in the present series, we chose to present estimated blood loss (EBL) as a descriptive variable, rather than as a potential complication

based on an arbitrary threshold. Complications were classified as minor or major, with the latter group including the complications that involved invasive intervention or had prolonged or permanent morbidity.

At the time of enrollment, standing long-cassette radiographs as well as cervical anterior–posterior and lateral radiographs were obtained. All spine radiographs were analyzed using validated software (Spineview®, ENSAM Laboratory of Biomechanics, Paris) [16] at a central location based on standard techniques [2]. The following protocol was applied for radiographic assessment. First, a trained reader identified key anatomic spinal landmarks that were subsequently used by the software to generate measurements. A second trained reader then reviewed and confirmed the identification of the key anatomic landmarks. Any discrepancies were resolved through joint review of the two readers. Any subsequent follow-up imaging for patients included a review of all previous imaging for the respective patient to ensure anatomic landmark and measurement consistency.

All alignment parameters were assessed based on standing radiographs. Long-cassette standing radiographs were used for assessment of global sagittal alignment based on the sagittal vertical axis (SVA; C2 or C7 plumbline relative to the postero-superior corner of S1; C2-S1 SVA and C7-S1 SVA, respectively). Thoracic kyphosis (TK; T4-T12), pelvic tilt (PT), pelvic incidence (PI), coronal Cobb angles, C2-C7 SVA, cervical lordosis (CL; C2-C7), and T1 slope (TS) were measured as previously described [1, 2, 17]. In addition, regional sagittal alignment parameters spanning the 3CO levels were assessed, including C2-T4 sagittal Cobb angle, C2-T4 SVA, C7-T4 sagittal Cobb angle, and C7-T4 SVA. The mismatch between the TS and CL (TS-CL) was calculated. The mismatch between the TS and CL has been suggested as an analogous parameter to the PI-LL mismatch, since a greater TS requires a greater magnitude of CL to balance the head over the trunk just as a greater PI necessitates a greater LL for harmonious alignment [1, 3]. Cervical deformity type was classified based on the Ames-Smith cervical spine deformity classification (Fig. 1).

Data analysis

Demographic, clinical, surgical and radiographic variables were summarized using means and standard deviations for continuous variables and frequencies and percentages for categorical variables. Paired t tests were used to assess for differences in alignment measures between follow-up and baseline radiographs. Statistical analyses were performed using SPSS version 22.0 (IBM). Statistical tests were two-tailed, and a p value of <0.05 was considered statistically significant.

Results

Baseline demographic and radiographic parameters

Of 121 ACD patients enrolled in the prospective database at the time of extraction for the present study, 23 (19%) had a 3CO as part of the surgical treatment for cervical or cervicothoracic deformity. These 23 patients were enrolled between April 2013 and May 2015, and all had achieved 90-day follow-up at the time of data extraction. Patients that met study criteria were from 7 institutions (14 from one center, 3 from one center, 2 from one center, and 1 each from 4 centers). Table 1 summarizes the demographic and operative parameters for the 23 3CO patients. The mean age was 62.3 years, and the majority (70%) of patients were women. The mean body mass index (BMI) of 31.9 corresponds to class I obesity. The mean Charlson Comborbidity Index (CCI) was 0.8, indicating that on average each patient had one of the major comorbidities listed in the CCI. Only one patient (4.3%) was an active smoker at the time of enrollment.

Twelve (52.2%) patients had a history of previous cervical/cervicothoracic instrumentation. Of these 12 patients, 8 had prior combined anterior and posterior fusion, 3 had prior posterior-only fusion, and 1 had prior anterior-only fusion. Of the 9 patients with previous anterior fusion (either anterior-only or as part of a combined anterior-posterior procedure), the mean number of anterior cervical/cervicothoracic fusion levels was 3.3 (SD 1.1, range 2–5), and of the 11 patients with previous posterior fusion (either posterior-only or as part of a combined anterior-posterior procedure), the mean number of posterior cervical/cervicothoracic fusion levels was 4.6 (SD 1.8, range 2–8). The remaining 11 (47.8%) patients had prior posterior thoracic/thoracolumbar instrumented fusion, with a mean number of vertebral levels of 11.6 (SD 5.6, range 4–17).

Baseline radiographic parameters are summarized in Table 2. The mean global alignment, as assessed by the C2-S1 SVA and C7-S1 SVA, was not markedly abnormal; however, the standard deviations were high and the ranges of values were very broad (Table 2). The distribution of deformity types is shown in Fig. 1. The most common type was CT (cervical kyphotic deformity with an apex at the cervicothoracic junction, Fig. 1b, e), which accounted for 43.5% of cases.

Operative parameters and complications with 90 days

Operative parameters are summarized in Table 1. By selection, all patients were treated with a posterior surgical approach (mean number of 12 vertebral levels

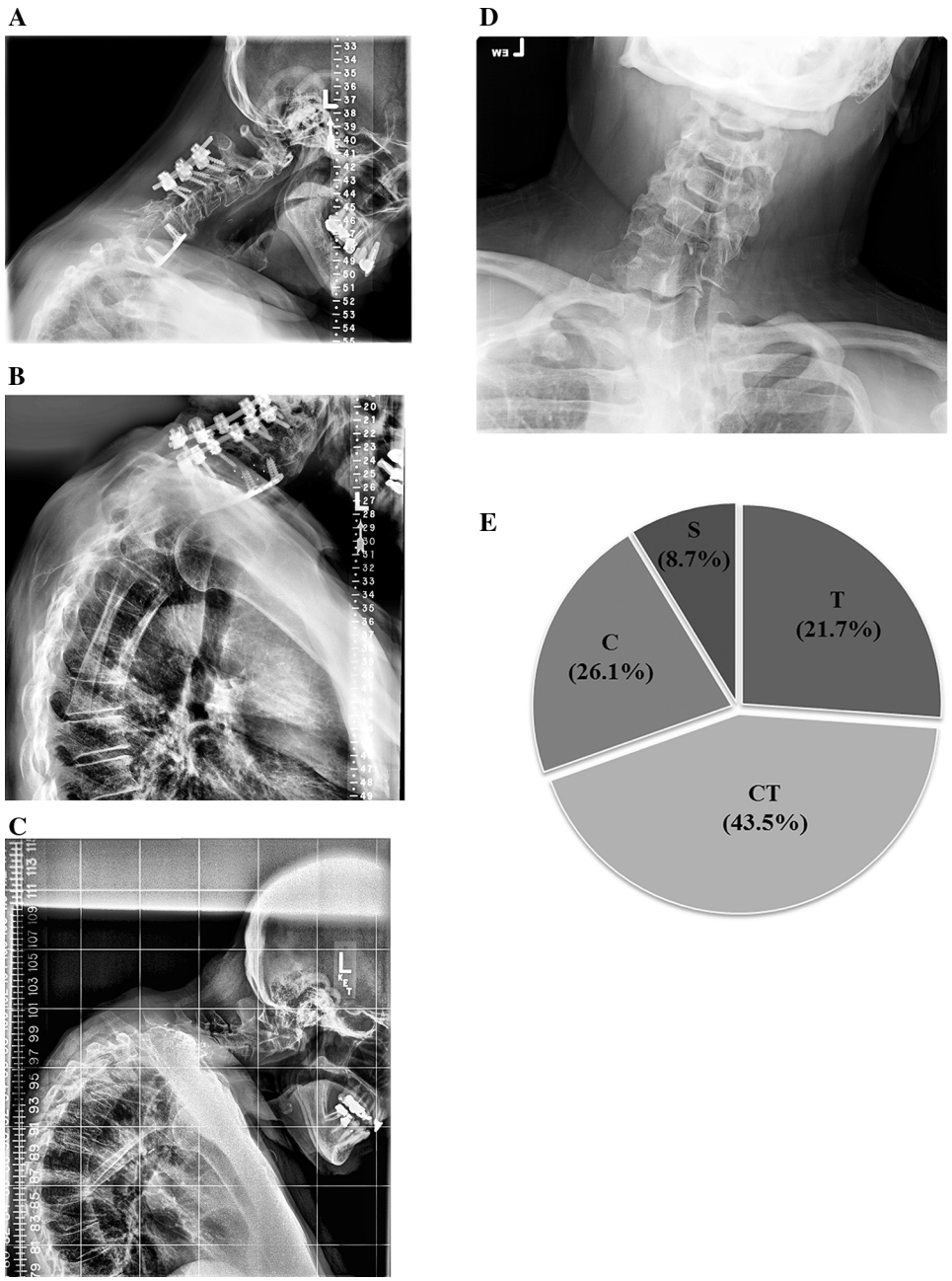

Fig. 1 Ames-Smith cervical deformity types [3] and distribution of study cases by deformity type. Shown are radiographs of Type C (cervical kyphotic deformity with an apex in the mid-cervical region **a**), Type CT (cervical kyphotic deformity with an apex at the cervicothoracic junction **b**), Type T (cervical kyphotic deformity with an apex in the thoracic region **b**), and Type S (primary coronal deformity **d**). Also shown is a *pie chart* summarizing the distribution of 24 adult cervical deformity cases in the present series by type (**e**)

instrumented and arthrodesed and a range of 6-18 levels), and one patient also had an anterior procedure (5 levels). The 23 3COs include 14 (61%) PSOs and 9 (39%) VCRs. The vertebral levels for the PSOs were: C7 ($n = 1$), T1 ($n = 9$), T2 ($n = 3$), and T3 ($n = 1$), and VCR vertebral levels were: T2 ($n = 4$), T3 ($n = 4$), and T4 ($n = 1$). Overall, the most common levels for 3CO were: T1 ($n = 9$, 39.1%), T2 ($n = 7$, 30.4%), and T3 ($n = 5$, 21.7%). None of the procedures were staged.

Early complications (operative through 90-day follow-up) are summarized in Table 3. There were 12 major and 6 minor complications. The mean number of major complications per patient was 0.52 and 9 patients (39.1%) had at least one major complication. The mean

Table 1 Demographic and operative parameters for 23 adults surgically treated for cervical spinal deformity with a three-column osteotomy

	Mean (SD)	Number (%)
Mean age, years	62.3 (9.7)	
Female: male		16 (70): 7 (30)
Mean body mass index	31.9 (8.8)	
Mean Charlson comorbidity index	0.8 (1.1)	
Current smoker		1 (4.3)
Previous cervical/cervicothoracic fusion		12 (52.2)
Previous thoracic/thoracolumbar fusion		11 (47.8)
Anterior procedure (*n*)		1 (4.3)
Levels	5 (NA)	
Posterior procedure, (*n*)		23 (100)
Mean levels instrumented/arthrodesed, range	12, 6–18 (3)	
PSO:VCR		14 (61): 9 (39)
Mean operating room time (h)	5.8 (2.5)	
Mean estimated blood loss (L)	1.3 (0.8)	
Mean hospital stay (days)	7.5 (3.4)	

SD standard deviation, *PSO* pedicle subtraction osteotomy, *VCR* vertebral column resection

Table 2 Comparison of pre- and postoperative radiographic parameters in 24 adults with cervical deformity treated with three-column osteotomy

	Baseline, mean (SD, range)	Postoperative, mean (SD, range)	*p* value
C2–C7 lordosis (°)	2.8 (23.7, −28 to 67)	12.7 (21.2, −34 to 69)	**0.031**
T1 slope (°)	48.1 (16.1, 21–81)	40.5 (17.7, 13–85)	**0.024**
T1 slope minus C2–C7 lordosis (°)	46.2 (17.9, 14–78)	27.3 (8.2, 15–79)	**<0.001**
C2–C7 SVA (mm)	65.7 (17.6, 41–92)	43.6 (11.7, 27–67)	**<0.001**
Thoracic kyphosis (T4–T12) (°)	−43.6 (22.4, −81 to 0)	−46.3 (21.3, −89 to 2)	0.16
C2–S1 SVA (mm)	73.9 (75.4, −25 to 259)	72.9 (79.0, −24 to 225)	0.91
C7–S1 SVA (mm)	0.4 (69.9, −119 to 171)	30.5 (71.2, −93 to 184)	**<0.001**
Pelvic tilt (°)	23.2 (11.3, 5–52)	22.2 (9.8, 6–39)	0.36

SD standard deviation, *SVA* sagittal vertical axis, significant *p* values are shown in bold

number of minor complications per patient was 0.26 and 6 patients (26.1%) each had one minor complication. Overall, 13 patients (56.5%) had at least one minor or major complication. Most patients that experienced a complication only had a single complication, with fewer patients having multiple complications (Fig. 2). The most common complications were neurologic and included 3 nerve root motor deficits, one of which required re-operation. Other neurologic complications included new nerve root sensory deficit ($n = 1$), radiculopathy ($n = 1$) and mental status change ($n = 2$). Three major cardiorespiratory complications occurred, including 2 cardiorespiratory failures and a non-fatal pulmonary embolism. One patient had an implant-related complication, which was prominence, and this required re-operation. There were 2 superficial wound infections, and no deep wound infections. Within the first 90 days of surgery, 2 patients developed significant distal junctional kyphosis, one of which necessitated re-operation. Remaining complications included 1 patient with ileus and a patient with significant dysphagia.

Comparison of postoperative alignment with baseline measures

Table 2 provides a summary of postoperative radiographic alignment parameters and statistical comparisons with respective baseline values. Following surgery, the mean C2-C7 lordosis increased significantly, the mean T1 slope decreased significantly, and the mean mismatch between the T1 slope and C2-C7 lordosis (TS-CL) decreased significantly. Postoperative imaging showed significant reduction of the mean C2-C7 SVA. Regional sagittal alignment spanning the 3CO levels also significantly

Table 3 Rates of early (within 90 days of surgery) complications in 23 adults with surgical treated that included a three-column osteotomy for cervical spinal deformity

Complication Category	Major (%)	Minor (%)	Total minor and major (%)
Neurologic	5 (21.7)	3 (13.0)	8 (34.8)
Nerve root motor deficit (not C5)	2 [1 re-op]	0	2 (8.7)
C5 motor deficit	1	0	1 (4.3)
Nerve root sensory deficit	1	0	1 (4.3)
Radiculopathy	1	0	1 (4.3)
Mental status change	0	2	2 (8.7)
Other	0	1	1 (4.3)
Cardiopulmonary	3 (13.0)	0 (0)	3 (13.0)
Cardiorespiratory failure	2	0	2 (8.7)
Pulmonary embolism	1	0	1 (4.3)
Infection	0 (0)	2 (8.7)	2 (8.7)
Deep wound infection	0	0	0
Superficial wound infection	0	2	2 (8.7)
Radiographic	2 (8.7)	0 (0)	2 (8.7)
Distal junctional kyphosis	2 [1 re-op]	0	2 (8.7)
Implant	1 (4.3)	0 (0)	1 (4.3)
Implant pain/prominence	1 [1 re-op]	0	1 (4.3)
Dysphagia/dysphonia	1 (4.3)	0 (0)	1 (4.3)
Dysphagia	1	0	1 (4.3)
Gastrointestinal	0 (0)	1 (4.3)	1 (4.3)
Ileus	0	1	1 (4.3)
Total complications	12	6	18
Mean number of complications/patient	0.52	0.26	0.78
Number of patients affected (%)	9 (39.1)	6 (26.1)	13 (56.5)

The number of re-ops indicates the subset of indicated major complications that were associated with the need for re-operation

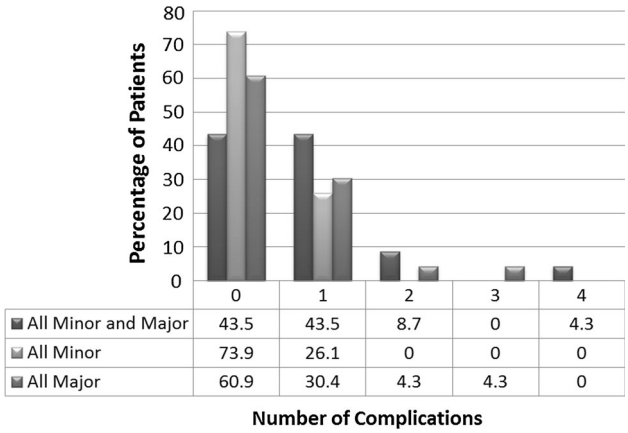

Fig. 2 Distribution of patients based on the numbers of minor and major complications that occurred within 90 days of surgery

improved based on the C2-T4 sagittal Cobb angle, C2-T4 SVA, C7-T4 sagittal Cobb angle, and C7-T4 SVA. There was a modest but significant increase of the mean C7-S1 SVA. There were no significant changes between postoperative and baseline imaging for thoracic kyphosis, C2-S1 SVA, or PT. A case example of a 68-year-old woman treated with a 3CO at the T2 vertebral level is shown in Fig. 3.

Discussion

The present study provides an assessment of a prospectively collected multicenter series of 23 ACD patients treated with a 3CO for cervical or cervicothoracic deformity. The affected population had a mean age of 62 years and the majority of patients (70%) were women. On average, patients had one of the major complications listed in the CCI, and the mean BMI corresponded to class I obesity. Notably, more than one-half (52.2%) of patients had a history of previous cervical/cervicothoracic fusion, and almost one-half (47.8%) had a history of prior thoracic/thoracolumbar fusion. The vast majority of deformities (91.3%) were kyphoses, with the most common apex at the cervicothoracic junction (43.5%), followed by an apex in the mid-cervical (26.1%) or thoracic (21.7%) region. Primary coronal deformities accounted for only 8.7% of cases. The most common vertebral levels for the 3CO were in the

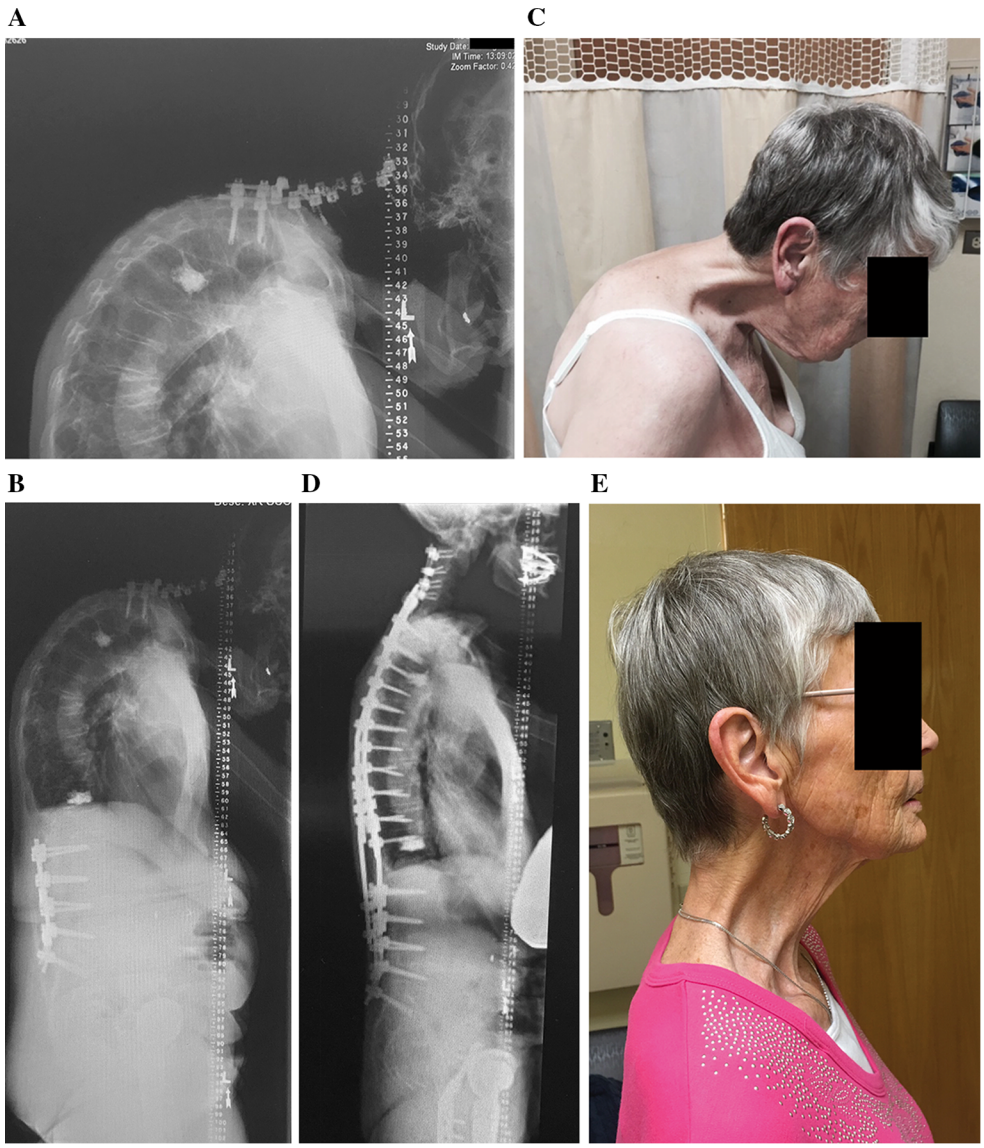

Fig. 3 Case example of 68-year-old woman treated with a three-column osteotomy for chin-on-chest cervical deformity. This patient provided consent for publication of her images. Shown are lateral cervical (**a**) and full-length lateral (**b**) standing radiographs that demonstrate prior cervicothoracic and lumbo-sacral instrumented fusions, respectively. Subsequently, she developed progressive chin-on-chest cervical deformity (**c**) and underwent a pedicle subtraction osteotomy at the T2 vertebra with extension of the cervicothoracic instrumentation and connection to the lumbo-sacral instrumentation with good radiographic (**d**) and clinical (**e**) correction of her deformity

upper thoracic spine, with only one 3CO performed at a cervical level. Early complication rates (within 90-days) were high, with 12 major and 6 minor complications. The most common complications were neurologic and were primarily radicular. Measures of cervical and cervicothoracic alignment improved significantly following surgery, including C2-C7 lordosis ($p = 0.036$), TS-CL ($p < 0.001$), C2-C7 SVA ($p < 0.001$), C7-T4 sagittal Cobb angle ($p < 0.001$), and C7-T4 SVA ($p = 0.014$).

The rates of complications identified in the present study are relatively high compared with previous reports. Overall, 18 complications (12 major and 6 minor) were identified, and 56.5% of patients experienced at least one complication. When comparing the rates of complications of the present study with previous reports, it is important to recognize key differences in study design. The present study was prospective, utilized standardized data collection forms for complication collection, had study coordinators at each site to review and collect complications, and had regular auditing of the complications data at a central core facility. The most common complications were neurologic, with radicular motor and sensory deficits predominating, and no spinal cord complications encountered. Notably, there was a considerable range for operative blood loss in

this series (0.25–3.0 L); however, there were no apparent associated complications or consequences of the excessive blood loss noted in these patients. Whether excessive blood loss without apparent sequelae should be considered a complication in spine surgery remains controversial and thresholds for this determination remain arbitrary. We chose to describe blood loss descriptively (mean, standard deviation, range), rather than as a potential complication, which is consistent with most previous reports. Notably, the mean EBL in the present series (1.3 L) is lower than that reported by Tokala and colleagues, who reported a mean blood loss of 2.4 L (range 1–3.2 L) in their series of 8 patients treated with C7 PSO for fixed cervicothoracic kyphosis [18].

There are few previous reports for comparison of complication rates and all are retrospective. Deviren et al. reported on 11 patients treated with cervicothoracic junction PSO for cervical sagittal imbalance [13]. They noted 2 cases of pneumonia, 1 patient with severe dysphagia requiring a percutaneous endoscopic gastrostomy, and a patient with rod fracture at 4 months following surgery, but did not encounter any neurological complications. Tokala and colleagues reported on 8 patients treated with C7 PSO for fixed cervicothoracic kyphosis and reported that 3 patients had mild C8 sensory radiculopathy that resolved within 4 weeks and 2 patients had deep wound infections [18]. Samudrala et al. reviewed 8 patients treated with PSO for cervicothoracic junction kyphosis and reported that 2 patients had hand numbness and weakness that resolved and 1 patient developed right upper extremity weakness on postoperative day one that required exploration and nerve root decompression [19]. Theologis and colleagues reported 34 complications that occurred in a retrospective review of 45 patients treated with a 3CO for cervicothoracic kyphosis correction [6]. This included 11 patients (23%) that required re-operation for multiple reasons, including new neurologic deficit, pseudarthrosis, instrumentation failure, and deep wound infection.

In a literature review of the surgical management of cervical or cervicothoracic kyphosis due to ankylosing spondylitis, Etame and colleagues identified 6 retrospective studies with complication rates ranging from 26.9 to 87.5% [20]. However, the majority of patients in their review were treated with the original Simmons opening-wedge osteotomy [11, 21], whereas the present study primarily utilized closing wedge PSOs and VCRs. Closing wedge osteotomies offer several advantages over opening-wedge osteotomies, including greater stiffness, greater bony surface area for fusion, and potentially greater stability with lower risk of subluxation [5, 22].

A recent report from Kim and colleagues detailed their series of cervical osteotomies for the treatment of fixed cervical deformity in patients with myelopathy [23]. Of the 35 patients described in their series, 31 were treated with anterior osteotomies (with or without additional posterior instrumentation) and 4 underwent a posterior 3CO. They noted that the posterior 3CO technique resulted in greater angular corrections compared to anterior osteotomies, but that both patient groups demonstrated similar translational corrections and improvements in Neck Disability Index scores.

In contrast to previous reports that primarily described C7 3COs for correction of ACD [13, 18], in the present study only one 3CO was performed in the cervical spine (C7). Selection of the level for the 3CO is multifactorial and may in some cases be dictated by the deformity characteristics. In contrast to upper thoracic levels, the vertebral arteries may enter the transverse foramen in a subset of patients at the C7 level and introduce increased risk of vascular compromise with a C7 3CO. An additional consideration is the functionality of the nerves at and adjacent to the level of the osteotomy. The C7, C8, and T1 nerves have important sensory and motor function and are at potential risk with 3COs performed at the C7 and T1 levels. Given the potentially enhanced safety of performing the 3CO at more caudal levels, several of the co-authors of the present study have progressively shifted to performing 3COs at the T2 and T3 vertebral levels when feasible.

Following surgery, cervical alignment improved significantly, as reflected by an increase in the mean C2-C7 lordosis and a decrease in the mean C2-C7 SVA. Although normative values for cervical lordosis have been reported [1, 17], correlations between cervical lordosis and measures of health-related quality of life, as well as thresholds for clinical significance, have not been well defined. Analogous to the PI-LL mismatch, the TS-CL has been suggested to better reflect sufficiency of cervical lordosis [1, 3, 24]. The significant decrease in the mean mismatch between the TS and CL (from 46.4° to 27.0°, $p < 0.001$) suggests that a more harmonious cervical lordosis was achieved following surgery. Since most of the 3COs were performed in the upper thoracic spine, the overall improvement in CL may at least partially reflect realignment achieved through subaxial cervical instrumentation. Regional alignment spanning the 3CO levels significantly improved as assessed by the C2-T4 and C7-T4 sagittal Cobb angles and by the C2-T4 and C7-T4 SVA. For the C2-C7 SVA, Tang et al. reported a threshold of 40 mm for moderate disability [25]. Although the postoperative C2-C7 SVA in the present study remained near the threshold of 40 mm, it represents a significant improvement from the preoperative value (64.6 mm–42.3 mm, $p < 0.001$). The modest but significant increase in C7-S1 SVA following surgery may partially reflect relaxation of compensatory measures [26].

The primary strength of the present study is the prospective multicenter design with a standardized collection of detailed clinical and radiographic data. In addition, the patient cohort is heterogeneous and represents a broad spectrum of cervical deformities treated by multiple surgeons across multiple institutions, which enhances the generalizability of the findings. The primary limitation of the present study relates to the number of patients. Although a cohort of 23 ACD patients treated with 3CO is substantial compared with the numbers of patients in previous reports and in light of the relatively uncommon need for use of 3CO in ACD, there remain limitations in the ability to provide granular assessments of the data. In addition, the present study focuses on early complications and radiographic alignment changes. It is important to recognize that focusing on early complications likely underestimates some complications such as distal junctional failure, pseudarthrosis, and instrumentation failure. As our data mature, we anticipate further study to assess long-term complications and durability of the improvement in cervical alignment observed following surgery. Furthermore, with additional follow-up, we anticipate the ability to assess the impact of the surgical treatment on health-related quality of life. The outcomes and overall complication rates will only be realized with long-term follow-up.

Conclusions

The present study provides an assessment of a prospectively collected multicenter series of 23 ACD patients treated with a 3CO for cervical or cervicothoracic deformity. The baseline demographic and clinical data define a population that is predominantly elderly with major comorbidities and a high proportion with a history of previous spine surgery. Cervical or cervicothoracic kyphosis accounted for the majority of cases and most 3COs were performed at upper-thoracic levels. Although the resulting early complication rates were high, significant improvement in cervical alignment was achieved.

Compliance with ethical standards

Disclosure of funding The International Spine Study Group (ISSG) is funded through research grants from DePuy Synthes.

Conflict of interest Please see following 3 pages for COI disclosures for each author. Justin S. Smith, MD, PhD, Zimmer Biomet: consultant, honorarium for teaching, royalties; Nuvasive- consultant, honorarium for teaching; Cerapedics: consultant; K2 M: honorarium for teaching; AOSpine: fellowship funding; NREF: fellowship funding. Christopher Shaffrey, MD, Medtronic: royalties, patents, consultant; Nuvasive: royalties, patents, consultant, stock holder; Zimmer Biomet: royalties, patents, consultant; K2 M: consultant; Stryker: consultant; In Vivo: consultant; NIH: grants; Department of Defense: grants; ISSG: grants; DePuy Synthes: grants; AO: grants. Renaud Lafage, MS, none. Virginie Lafage, PhD, Depuy Synthes: paid lectures; Nuvasive: paid lectures; K2 M: paid lectures; Medtronic: paid lectures; Nemaris: Board member and shareholder. Frank Schwab, MD, Grants: SRS, DePuy Spine (through ISSGF); Speaking/teaching arrangements, consulting: Zimmer-Biomet, NuVasive, K2 M, MSD, Medicrea; Board of Directors, Share holder: Nemaris INC; Royalties: K2 M, MSD. Han Jo Kim, MD, K2 M: consultant; Zimmer Biomet: consultant; ISSGF: research funding; CSRS: research funding; HSS Journal: board membership; ASJ: board membership; GSJ: board membership. Justin Scheer, MD: none Themi Protopsaltis, MD, Consulting: Medicrea, Globus, Innovasis (money paid to me); Research support paid to my institution: Zimmer Spine. Peter Passias, MD, Medicrea: consultant. Gregory Mundis, MD, Nuvasive: consulting, royalties, research funding (not paid to Dr. Mundis); K2 M: consulting, royalties; DePuy Synthes: honorarium; DePuy Synthes/ISSG: research funding (not paid to Dr. Mundis). Robert Hart, MD, Globus: personal fees; Medtronic: grants; Seaspine: personal fees; DePuy Synthes: personal fees; CSRS: board member; ISSG:Executive Committee; ISSLS:board member; OHSU: patent. Brian Neuman, MD, Depuy Synthes: research grant. Eric Klineberg, MD, DePuy: consulting, Stryker: consulting, AOSpine: paid speaker, fellowship support, K2 M: paid speaker. Richard Hostin, MD, DePuy Synthes: consultant; Nuvasive: research support; Seeger: research support; DJO: research support. Shay Bess, MD, K2 Medical: consultant, royalties, research support; Allosource: consultant; Pioneer: royalties; Innovasis: royalties, research support; Nuvasive: royalties, research support; DePuy Synthes Spine: research support; Stryker: research support. Vedat Deviren, MD, Nuvasive: consultant, grants; Guidepoint: consultant; OREF: grants; AOSpine: grants; Globus: grants. Christopher P. Ames, MD, DePuy Synthes: consultant; Medtronic: consultant; Stryker: consultant, royalties; Zimmer Biomet: royalties; Fish & Richardson, PC: patents.

References

1. Scheer JK, Tang JA, Smith JS, Acosta FL Jr, Protopsaltis TS, Blondel B, Bess S, Shaffrey CI, Deviren V, Lafage V, Schwab F, Ames CP, International Spine Study G (2013) Cervical spine alignment, sagittal deformity, and clinical implications: a review. J Neurosurg Spine 19:141–159. doi:10.3171/2013.4.SPINE12838
2. Ames CP, Smith JS, Scheer JK, Bess S, Bederman SS, Deviren V, Lafage V, Schwab F, Shaffrey CI (2012) Impact of spinopelvic alignment on decision making in deformity surgery in adults: a review. J Neurosurg Spine 16:547–564. doi:10.3171/2012.2.SPINE11320
3. Ames CP, Smith JS, Eastlack R, Blaskiewicz DJ, Shaffrey CI, Schwab F, Bess S, Kim HJ, Mundis GM Jr, Klineberg E, Gupta M, O'Brien M, Hostin R, Scheer JK, Protopsaltis TS, Fu KG, Hart R, Albert TJ, Riew KD, Fehlings MG, Deviren V, Lafage V, International Spine Study G (2015) Reliability assessment of a novel cervical spine deformity classification system. J Neurosurg Spine. doi:10.3171/2014.12.SPINE14780
4. Ames CP, Smith JS, Scheer JK, Shaffrey CI, Lafage V, Deviren V, Moal B, Protopsaltis T, Mummaneni PV, Mundis GM Jr, Hostin R, Klineberg E, Burton DC, Hart R, Bess S, Schwab FJ, International Spine Study G (2013) A standardized nomenclature for cervical spine soft-tissue release and osteotomy for deformity correction: clinical article. J Neurosurg Spine 19:269–278. doi:10.3171/2013.5.SPINE121067
5. Belanger TA, Milam RA, Roh JS, Bohlman HH (2005) Cervicothoracic extension osteotomy for chin-on-chest deformity in ankylosing spondylitis. J Bone Jt Surg Am 87:1732–1738

6. Theologis AA, Tabaraee E, Funao H, Smith JS, Burch S, Tay B, Kebaish K, Deviren V, Ames C (2015) Three-column osteotomies of the lower cervical and upper thoracic spine: comparison of early outcomes, radiographic parameters, and peri-operative complications in 48 patients. Eur Spine J 24(Suppl 1):S23–S30. doi:10.1007/s00586-014-3655-6
7. Wollowick AL, Kelly MP, Riew KD (2012) Pedicle subtraction osteotomy in the cervical spine. Spine 37:E342–E348. doi:10.1097/BRS.0b013e318245bcd4
8. Smith JS, Sansur CA, Donaldson WF 3rd, Perra JH, Mudiyam R, Choma TJ, Zeller RD, Knapp DR Jr, Noordeen HH, Berven SH, Goytan MJ, Boachie-Adjei O, Shaffrey CI (2011) Short-term morbidity and mortality associated with correction of thoracolumbar fixed sagittal plane deformity: a report from the Scoliosis Research Society Morbidity and Mortality Committee. Spine 36:958–964. doi:10.1097/BRS.0b013e3181eabb26
9. Smith JS, Klineberg E, Lafage V, Shaffrey CI, Schwab F, Lafage R, Hostin R, Mundis GM Jr, Errico TJ, Kim HJ, Protopsaltis TS, Hamilton DK, Scheer JK, Soroceanu A, Kelly MP, Line B, Gupta M, Deviren V, Hart R, Burton DC, Bess S, Ames CP, International Spine Study G (2016) Prospective multicenter assessment of perioperative and minimum 2-year postoperative complication rates associated with adult spinal deformity surgery. J Neurosurg Spine. doi:10.3171/2015.11.SPINE151036
10. Mason C, Cozen L, Adelstein L (1953) Surgical correction of flexion deformity of the cervical spine. Calif Med 79:244–246
11. Simmons EH (1972) The surgical correction of flexion deformity of the cervical spine in ankylosing spondylitis. Clin Orthop Relat Res 86:132–143
12. Urist MR (1958) Osteotomy of the cervical spine; report of a case of ankylosing rheumatoid spondylitis. J Bone Jt Surg Am 40(4):833–843
13. Deviren V, Scheer JK, Ames CP (2011) Technique of cervicothoracic junction pedicle subtraction osteotomy for cervical sagittal imbalance: report of 11 cases. J Neurosurg Spine 15:174–181. doi:10.3171/2011.3.SPINE10536
14. Grosso MJ, Hwang R, Krishnaney AA, Mroz TE, Benzel EC, Steinmetz MP (2015) Complications and outcomes for surgical approaches to cervical kyphosis. J Spinal Disord Tech 28:E385–E393. doi:10.1097/BSD.0b013e318299953f
15. Han K, Lu C, Li J, Xiong GZ, Wang B, Lv GH, Deng YW (2011) Surgical treatment of cervical kyphosis. Eur Spine J 20:523–536. doi:10.1007/s00586-010-1602-8
16. Champain S, Benchikh K, Nogier A, Mazel C, Guise JD, Skalli W (2006) Validation of new clinical quantitative analysis software applicable in spine orthopaedic studies. Eur Spine J 15:982–991. doi:10.1007/s00586-005-0927-1
17. Ames CP, Blondel B, Scheer JK, Schwab FJ, Le Huec JC, Massicotte EM, Patel AA, Traynelis VC, Kim HJ, Shaffrey CI, Smith JS, Lafage V (2013) Cervical radiographical alignment: comprehensive assessment techniques and potential importance in cervical myelopathy. Spine 38:S149–S160. doi:10.1097/BRS.0b013e3182a7f449
18. Tokala DP, Lam KS, Freeman BJ, Webb JK (2007) C7 decancellisation closing wedge osteotomy for the correction of fixed cervico-thoracic kyphosis. Eur Spine J 16:1471–1478. doi:10.1007/s00586-006-0290-x
19. Samudrala S, Vaynman S, Thiayananthan T, Ghostine S, Bergey DL, Anand N, Pashman RS, Johnson JP (2010) Cervicothoracic junction kyphosis: surgical reconstruction with pedicle subtraction osteotomy and Smith-Petersen osteotomy. Presented at the 2009 Joint Spine Section Meeting. Clincal article. J Neurosurg Spine 13:695–706. doi:10.3171/2010.5.SPINE08608
20. Etame AB, Than KD, Wang AC, La Marca F, Park P (2008) Surgical management of symptomatic cervical or cervicothoracic kyphosis due to ankylosing spondylitis. Spine 33:E559–E564. doi:10.1097/BRS.0b013e31817c6c64
21. Simmons EH, Brown ME (1972) Surgery for kyphosis in ankylosing spondylitis. Can Nurse 68:24–29
22. Scheer JK, Tang JA, Buckley JM, Deviren V, Pekmezci M, McClellan RT, Ames CP (2011) Biomechanical analysis of osteotomy type and rod diameter for treatment of cervicothoracic kyphosis. Spine 36:E519–E523. doi:10.1097/BRS.0b013e3181f65de1
23. Kim HJ, Nemani VM, Daniel Riew K (2015) Cervical osteotomies for neurological deformities. Eur Spine J 24(Suppl 1):S16–S22. doi:10.1007/s00586-014-3656-5
24. Lee SH, Kim KT, Seo EM, Suk KS, Kwack YH, Son ES (2012) The influence of thoracic inlet alignment on the craniocervical sagittal balance in asymptomatic adults. J Spinal Disord Tech 25:E41–E47. doi:10.1097/BSD.0b013e3182396301
25. Tang JA, Scheer JK, Smith JS, Deviren V, Bess S, Hart RA, Lafage V, Shaffrey CI, Schwab F, Ames CP, Issg (2012) The impact of standing regional cervical sagittal alignment on outcomes in posterior cervical fusion surgery. Neurosurgery 71:662–669. doi:10.1227/NEU.0b013e31826100c9 **discussion 669**
26. Klineberg E, Schwab F, Ames C, Hostin R, Bess S, Smith JS, Gupta MC, Boachie O, Hart RA, Akbarnia BA, Burton DC, Lafage V (2011) Acute reciprocal changes distant from the site of spinal osteotomies affect global postoperative alignment. Adv Orthop 2011:415946. doi:10.4061/2011/415946