Are the Arbeitsgemeinschaft Für Osteosynthesefragen (AO) Principles for Long Bone Fractures Applicable to 3-Column Osteotomy to Reduce Rod Fracture Rates?

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Objective: The aim was to determine whether applying Arbeitsgemeinschaft für Osteosynthesefragen (AO) principles for external fixation of long bone fracture to patients with a 3-column osteotomy (3CO) would be associated with reduced rod fracture (RF) rates.

Summary of Background Data: AO dictate principles to follow when fixating long bone fractures: (1) decrease bone-rod distance; (2) increase the number of connecting rods; (3) increase the diameter of rods; (4) increase the working length of screws; (5) use multiaxial fixation. We hypothesized that applying these principles to patients undergoing a 3CO reduces the rate of RF.

Methods: Patients were categorized as having RF versus no rod fracture (non-RF). Details on location and type of instrumentation were collected. Dedicated software was used to calculate the distance between osteotomy site and adjacent pedicle screws, angle between screws and the distance between the osteotomy site and rod. Classic sagittal spinopelvic parameters were evaluated.

Results: The study included 170 patients (34 = RF, 136 = non-RF). There was no difference in age ($P = 0.224$), sagittal vertical axis correction ($P = 0.287$), or lumbar lordosis correction ($P = 0.36$). There was no difference in number of screws cephalad ($P = 0.62$) or caudal ($P = 0.31$) to 3CO site. There was a lower rate of RF for patients with > 2 rods versus 2 rods ($P < 0.001$). Patients with multiplanar rod fixation had a lower rod fracture rate ($P = 0.01$). For patients with only 2 rods (N = 68), the non-RF cohort had adjacent screws that trended to have less angulation to each other ($P = 0.06$) and adjacent screws that had a larger working length ($P = 0.03$).

Conclusions: A portion of AO principles can be applied to 3CO to reduce RF rates. Placing more rods around a 3CO site, placing rods in multiple planes, and placing adjacent screws with a larger working length around the 3CO site is associated with lower RF rates.

Key Words: rod fracture, adult spinal deformity, biomechanics, spinal instrumentation, 3-column osteotomy, scoliosis

(*Clin Spine Surg* 2022;35:E429–E437)

Received for publication December 26, 2020; accepted November 17, 2021.

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The International Spine Study Group (ISSG) is funded through research grants from DePuy Synthes (current), Nuvasive (current), K2M (current), Innovasis (past), Biomet (past), and individual donations.

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The range of motion and weight bearing capability of the spine both contribute to the stress placed on spinal fixation. When significant surgical correction occurs there is also an increase in vertebral-implant axial forces and sagittal bending moments on the rods.[1] The biomechanical forces required for stabilization of a 3-column osteotomy (3CO) are even more significant.[2–7] In this difficult biomechanical environment there must also be encouragement to form a fusion mass, which requires balancing the risks of stress-shielding that could restrain such bone formation based on the principles of Wolf's law.[8]

Rod fracture (RF) for adult spinal deformity (ASD) can be a debilitating condition requiring revision surgery in many instances. Smith et al has shown that the rate of RF for all ASD patients range from 6.8% to 9.0% and from 15.8% to 22.0% for patients following a PSO.[9,10] Furthermore, this study also outlined the substantial range of RF rates between national spine centers. This suggests that RF rates could also be influenced by variance in surgical technique. These technique variances include factors such as the type of rod contouring, radius of rod curvature, and rod configuration.[7,11]

Similar to a 3CO site, there are profound biomechanical forces across long bone fractures.[12,13] Subtrochanteric femur fractures, for instance are under significant bending, torsional and compressive forces that can make stabilization/union a surgical challenge.[14,15] Arbeitsgemeinschaft für Osteosynthesefragen (AO) is an organization that was originally created to research and innovate in the field of bone healing.[16,17] There are AO principles for external fixation of long bone fracture which are commonly followed by surgeons throughout the world. These include for external fixators (1) decreasing bone-rod distance; (2) increasing the number of connecting rods; (3) increasing the diameter of rods; (4) increasing the working length of screws; and (5) using multiaxial fixation.

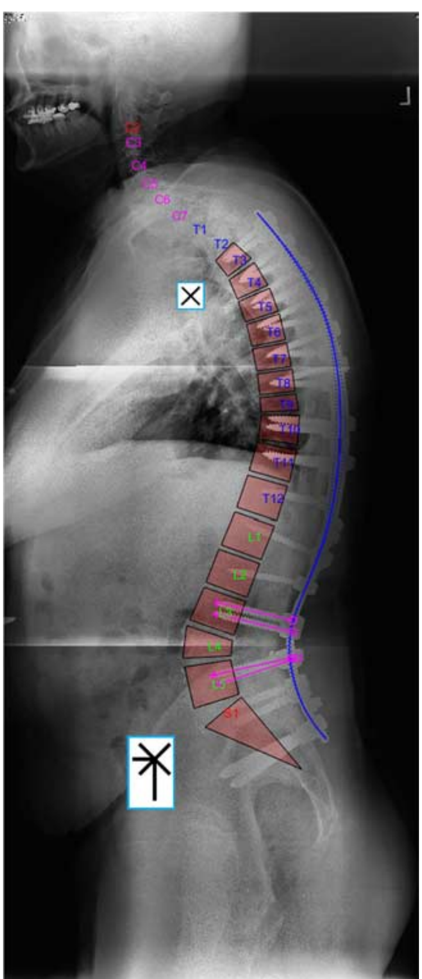

FIGURE 1. Standing calibrated radiographs were used for our measurements. Each vertebral body in the thoracic and lumbar spine are outlined and shaded. The rod contour was marked in blue. The adjacent screws to the osteotomy site are marked in pink.

Given the harsh biomechanical environment that both a 3CO site and a long bone fracture share, we hypothesize that application of AO principles of external fixation may predict implant failure across a 3CO site. Our endpoint for this analysis is RF. We focused on AO parameters for external fixation including the number of fixation points (ie, pedicle screws) surrounding a 3CO site, rod diameter, number of rods, working length of adjacent pedicle screws, whether or not rods were placed in a uniaxial or multiaxial configuration and the number of rods surrounding a 3CO site.[17] Specific to 3CO fixation we also examined whether use of an interbody cage/device influenced RF rates. Our hypothesis is that constructs, which utilize AO principles for external fixators in their configuration for 3CO reconstructions, will have lower rates of RF.

METHODS

We performed a retrospective review of a prospectively collected database of adult patients over 18 years old. This database is a prospective collection of clinical/radiographic data from 11 centers across the United States. All patients were enrolled into an Institutional Review Board-approved protocol by each site. The inclusion criteria for this database was presence of spinal deformity defined as a coronal Cobb angle of >20 degrees, sagittal vertical axis (SVA) of >5 cm, pelvic tilt of >25 degrees and/or thoracic kyphosis >60 degrees. We only included patients that had a full 2 years of follow up with clinical evaluation and radiographs.

Within this database we selected for patients that underwent a 3CO. This would include patients that underwent a pedicle-subtraction osteotomy or a vertebral column resection osteotomy. All patients were required to have preoperative and follow up measurements of SVA, lumbar lordosis (LL), pelvic tilt (PT), and pelvic incidence (PI).

One of our team members (R.L.) designed software to examine rod configuration and orientation on calibrated standing scoliosis radiographs. We outlined the rod and screws adjacent to the 3CO site using this software. An example image is shown in Figure 1.

Postoperative radiograph for each patient was examined for RF either at the 3CO site or adjacent to it. If instrumentation failure occurred 2 or more levels cephalad or caudal to the 3CO from the 3CO site this patient was excluded from the study. The number of rods, use of an interbody at the osteotomy site, material of the rod and diameter of the rod were recorded. Postoperative radiographs were also examined to determine if the rods were placed in different planes on both AP and lateral radiographs when more than 2 rods were used in the construct If this was the case, the rods were deemed to be "multiplanar." Radiographs representing a uniplanar construct are shown in Figure 2. Radiographs representing a multiplanar construct are shown in Figure 3. A cartoon depiction of the difference between multiplanar and uniplanar constructs is also shown in Figure 4. The

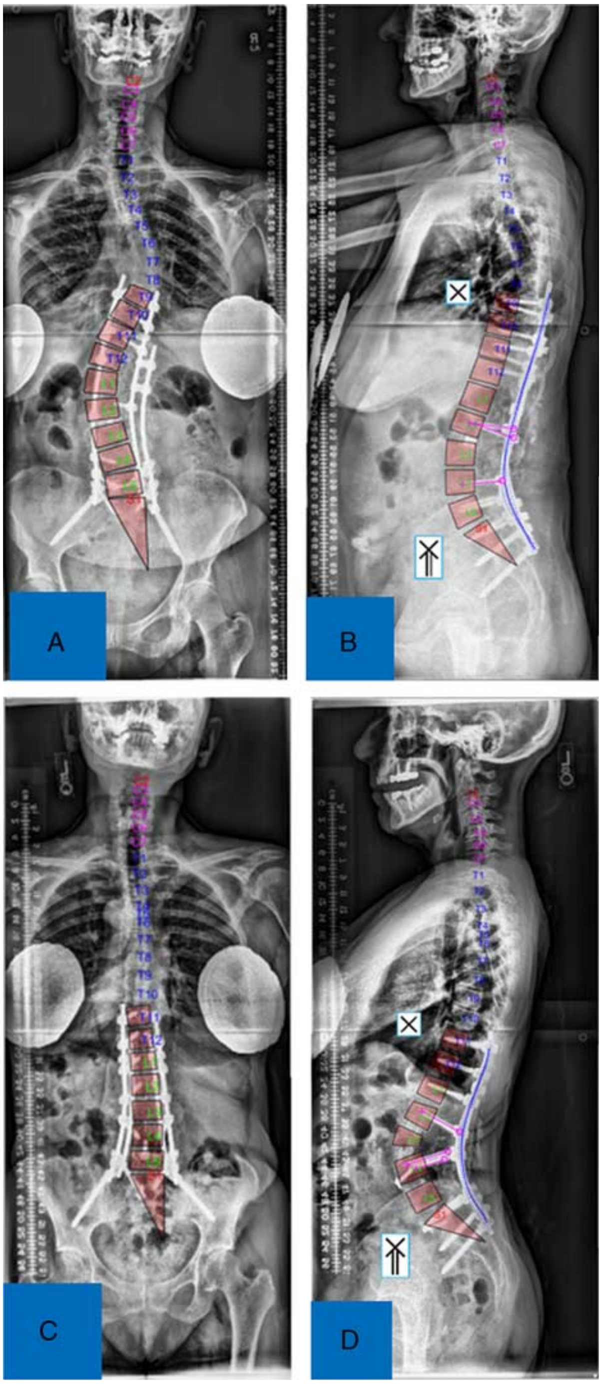

FIGURE 2. These 4 radiographs represent anterioposterior and lateral films from a uniplanar construct. A and B, Are from one patient and (C and D) are from a second patient. While on the anterioposterior radiograph one can differentiate between rods, there is no such distinction on the lateral radiograph. Multiple radiographs were examined to ensure that this finding was consistent.

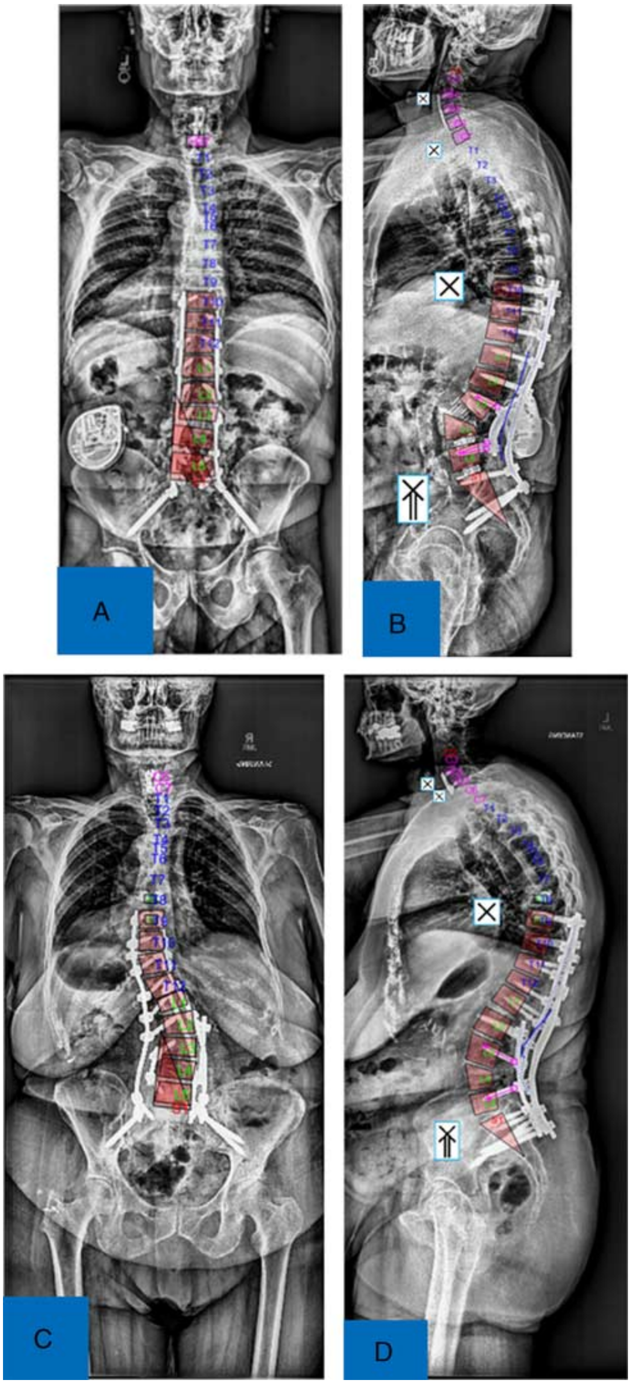

FIGURE 3. These 4 radiographs represent anterioposterior and lateral films from a multiplanar construct. On both anterioposterior and lateral radiographs one can differentiate between rods. A and B, Are from one patient and (C and D) are from a second patient.

number of screws placed above the osteotomy site and the number of screws placed below an osteotomy site were also recorded. Change in LL, SVA, and focal lordosis at the 3CO were measured based on preoperative and final radiographs for each patient. Using this specially designed software we were able to measure the angle between screws adjacent to an osteotomy site. An example measurement is shown in Figure 5. Acquisition of the

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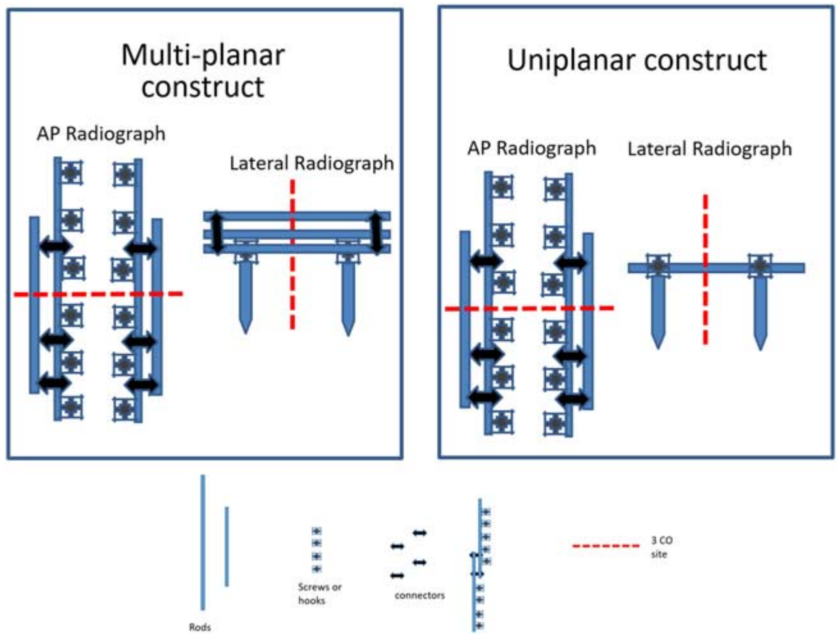

FIGURE 4. This is a depiction of our definition of a uniplanar versus multiplanar construct. Only when more than 2 rods were visualized on all anteriorposterior (AP) and lateral postoperative radiographs was a construct labeled as multiplanar.

rod shape was performed using Matlab 2017b (The Math Works Inc.) using a dedicated custom user interface (GUI). Points were taken manually and placed on the images along the rod (from one end to the other one) and a spine was to interpolate the shape between points. Postprocessing generation of all spine parameters, as well as rod parameters, was also done using Matlab 2017b.

Our software also allowed us to measure the distance between the rod and the posterior wall of the osteotomy site as well as the distance between the distance between the osteotomy site and the adjacent screws. These two measurements are shown in Figures 6 and 7. In order to isolate factors such as screw position in relation to the osteotomy site, the size of the rod, the type of the rod, and use of an interbody we performed a separate analysis on patients with only 2 rods.

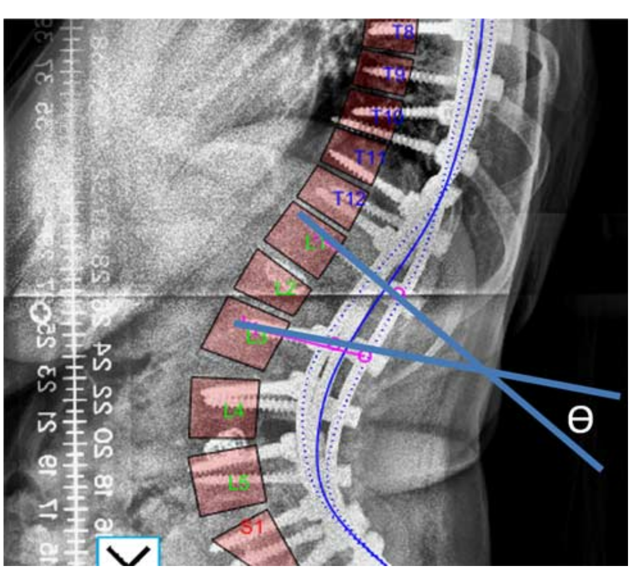

FIGURE 5. Angulation between screws was measured adjacent to the osteotomy site. The measured angle is marked as "θ."

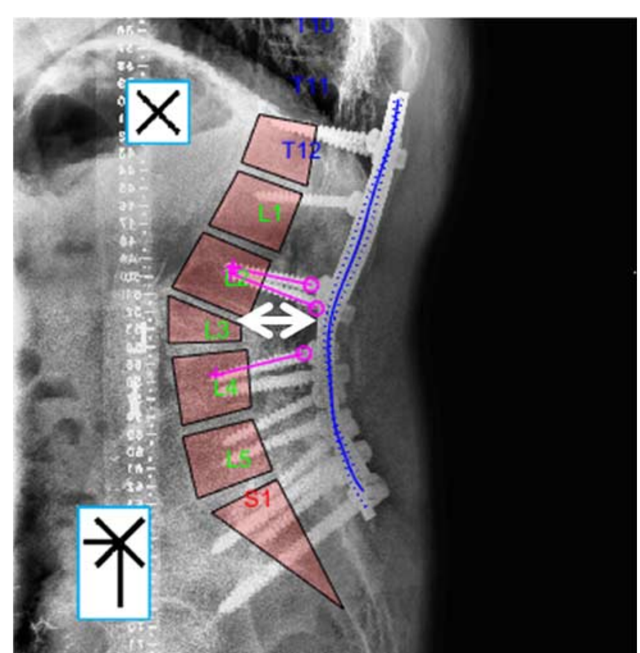

FIGURE 6. The distance between the osteotomy site and the rod is shown in white arrow.

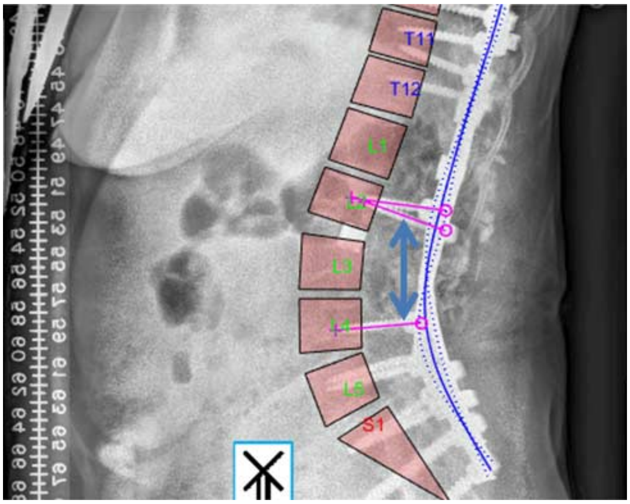

FIGURE 7. The distance between adjacent screws at an osteotomy site is shown in blue arrow.

Statistical Analysis

We used basic statistical analysis tools to determine statistically significant factors potentially associated with RF rates. When comparing continuous variables such as the distance between an osteotomy site and adjacent screw, a Student *t* test was used to compare cohorts. When comparing categorical variables, we used a χ^2 test. The level of significance was set at 0.05.

RESULTS

Of 196 patients with 3CO, we found 170 patients within our database that met inclusion criteria of at least 2-year follow up. Within the RF cohort there were 34 patients. Within the nonrod fracture cohort (non-RF) there were 136 patients. For the overall cohort of patients, the average age was 61.9 ± 12.4 years and there were 112 women and 58 men. The demographics of the 2 cohorts are shown in Table 1. Preoperative radiographic measurements are also listed in Table 1. Of note, there were no statistically significant difference between cohorts in terms of demographic variables or preoperative radiographic measurements.

TABLE 1. The Demographic Data for Our Cohort of Patients is Shown Along With Preoperative Radiographic Measurements

Demographic	Nonrod Fracture Cohort	Rod Fracture Cohort	*P*
Age (y)	62.8 ± 11.2	58.7 ± 16.0	0.16
Sex			
Female	65.4% (89 patients)	67.6% (23 patients)	0.81
Preoperative radiographic measurements			
SVA (mm)	13.6 ± 7.7	14.4 ± 6.7	0.56
PI (deg)	57.5 ± 14.6	60.4 ± 13.5	0.28
LL (deg)	20.2 ± 19.6	18.7 ± 17.5	0.66
PT (deg)	31.0 ± 9.6	33.4 ± 10.4	0.23

There are no statistically significant differences between the cohorts based on these data points.

LL indicates lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SVA, sagittal vertical axis.

TABLE 2. Changes Between Preoperative and Postoperative Radiographic Measurements

Measurement	Nonrod Fracture Cohort	Rod Fracture Cohort	*P*
Δ LL (deg)	33.2 ± 14.5	35.8 ± 14.0	0.35
Δ Focal lordosis (deg)	31.6 ± 12.1	32.6 ± 14.7	0.73
Δ SVA (mm)	−10.0 ± 6.3	−11.9 ± 5.7	0.36

LL indicates lumbar lordosis; SVA, sagittal vertical axis.

Postoperative corrections were compared between the two cohorts. There were no significant differences in terms of change in overall lumbar lordosis, focal lordosis at the osteotomy site or SVA at 2 years from surgery. These results are shown in Table 2. The distribution of angles of adjacent screws is shown in Figure 8A. The distribution of distances between adjacent screws is shown in Figure 8B.

The number of rods surrounding an osteotomy site did have a significant impact on RF rates. Patients with 2 rods had a higher RF rate (33.3%; n = 24) than those with more than 2 rods (10.8%; n = 11) surrounding an osteotomy site ($P < 0.001$). There was no statistically significant difference in the number of screws placed above the 3CO site (12.2 ± 5.8 in non-RF versus 11.3 ± 6.4 in RF cohort, $P = 0.46$) or the number of screws placed below the 3CO site (5.5 ± 2.1 in non-RF vs. 5.1 ± 1.9 in RF, $P = 0.35$). Multiplanar rod constructs were also found to have a lower rate of RF compared with those placed in a uniplanar manner. Patients with multiplanar rod placement

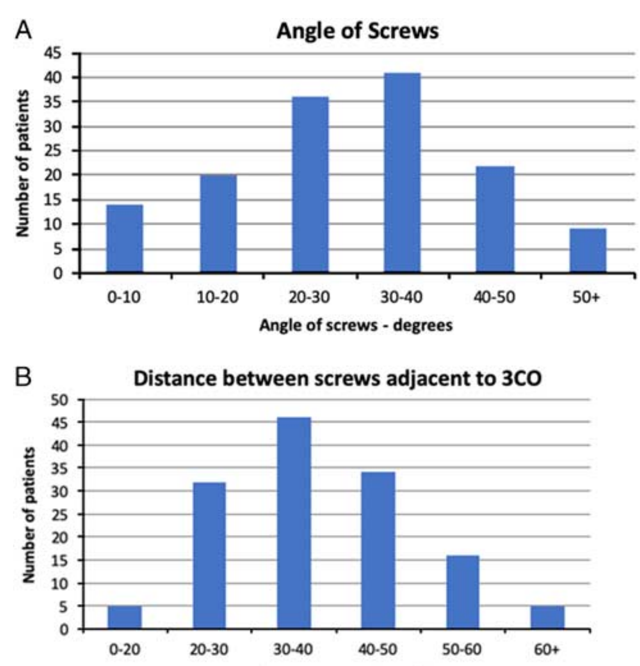

FIGURE 8. The distribution of angles between adjacent screws at a 3-column osteotomy (3CO) site is shown in (A). The distribution of distances between adjacent screws to 3CO sites is shown in (B).

TABLE 3. Patients With No Rod Fracture Were Found to Have Higher Working Length of Adjacent Screws and Decreased Angulation Between Adjacent Screws

Measurement	Nonrod Fracture Cohort	Rod Fracture Cohort	*P*
Angulation between adjacent screws (deg)	22.8 ± 13.3	30.8 ± 11.7	0.06
Working length of adjacent screws (mm)	43.3 ± 12.3	36.3 ± 8.3	0.03
Distance from rod to osteotomy site (mm)	40.5 ± 9.0	38.2 ± 8.3	0.62

had a fracture rate of 11.0% (n = 8) versus the 26.8% (n = 26) rate of RF for those that did not have multiplanar rod placement ($P = 0.01$).

There were 68 patients that were treated with 2 rods. We found a trend towards lower amount of angulation between adjacent screws and a significant difference in working length of adjacent screws to the 3CO site. We found that patients with a RF trended towards a higher angulation between adjacent screws (30.8 ± 11.7 vs. 22.8 ± 13.3 degrees, $P = 0.06$). We found patients with a RF had a statistically significant smaller distance between adjacent screws to a 3CO site (38.2 ± 8.3 vs. 40.5 ± 9.0 mm, $P = 0.03$). There was no significant difference in distance from rod-osteotomy site for our cohort of patients (40.5 ± 9.0 vs. 38.2 ± 8.3 mm, $P = 0.62$). These results are summarized in Table 3. Images demonstrating a 3CO with a small and large distance between screws adjacent to a 3CO site are shown in Figure 9.

Within our 2-rod cohort of patients there were 26 patients (38.2%) that had an interbody placed at the 3CO site (42 patients without an interbody). The rate of RF was lower for patients treated with an interbody, but this difference only approached but did not reach statistical significance Table 4.

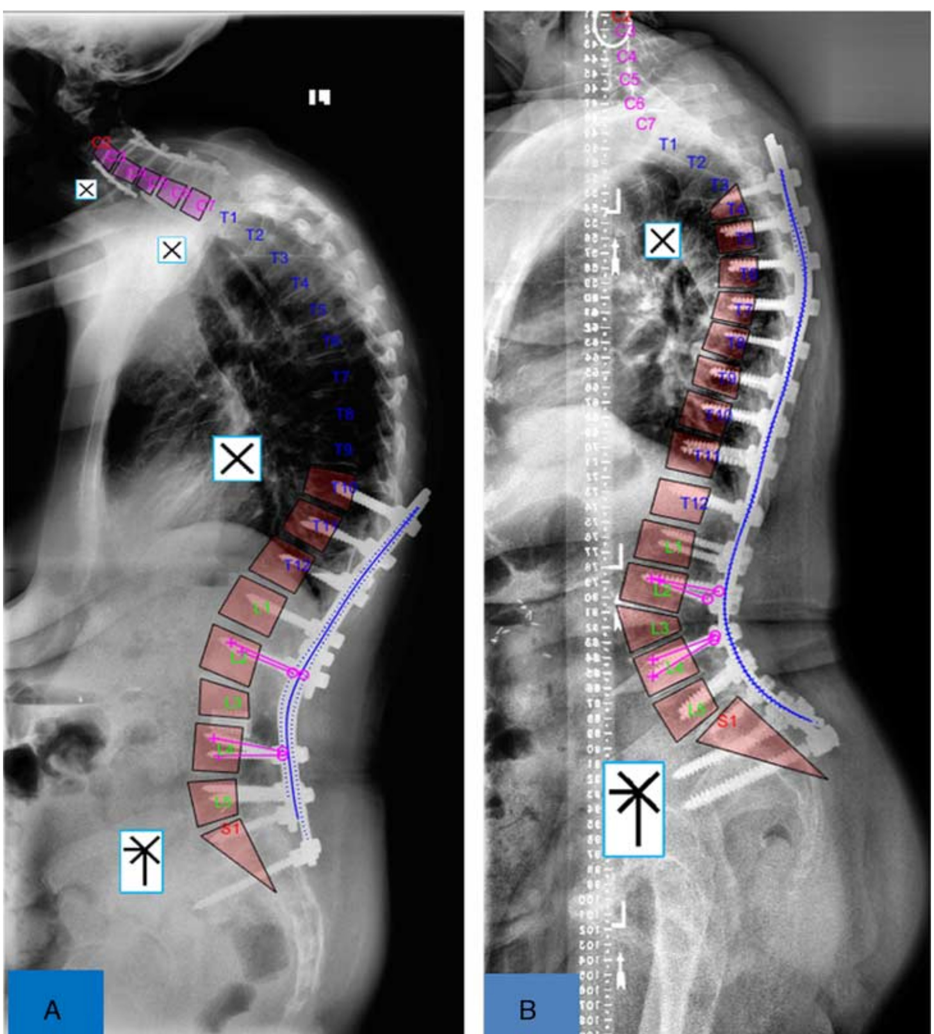

FIGURE 9. A large and a small distance between adjacent screws to a 3-column osteotomy (3CO) site is shown in these 2 radiographs. In (A) there is a large distance between adjacent screws at a 3CO site (6.0 cm). This contrasts with (B) which demonstrates screws closer together around a 3CO site (2.4 cm). Of note, the construct in (B) did go on to have a rod fracture.

TABLE 4. Whether an Interbody Was Placed, Rod Type and Rod Diameter Were Analyzed for Their Impact On Rod Fracture Rates in the Cohort of Patients Treated With 2 Rods

Operative Choice	Rod Fracture Rate
Interbody placement	
Interbody placed at 3CO site	23.1% (6/26 patients)
No interbody	18/42 (42.3%)
P	0.08
Rod type	
Cobalt chromium rods	16/36 (45.7%)
Non-Cobalt chromium rods	8/32 (25.0%)
P	0.08
Rod diameter	
6 mm or greater cobalt chromium rods	9/20 (45.0%)
< 6 mm cobalt chromium rods	15/47 (31.9%)
P	0.31

3CO indicates 3-column osteotomy.

For those patients treated with 2 rods, we did not find a significant difference in RF rate between those patients treated with cobalt chromium (CC) rods versus steel or titanium rods (non-CC). The rate of RF for CC was 45.7% (16/36) versus 25.0% (8/32) for non-CC ($P=0.08$). Similarly, we found no statistically significant difference in RF rate between patients treated with 6mm or greater rod diameter and CC versus those with smaller diameter and/or non-CC rods. The rate of RF for patients with a 6mm or greater diameter CC rod was 45.0% (9/20) versus 31.9% (15/47) which was not a statistically different ($P=0.3122$).

DISCUSSION

Our analysis demonstrates that the use of the AO principles can be applicable to fixation around a 3CO site. Increased working length of adjacent screws, increased rod number and usage of a multiplanar rod construct was associated with lower RF rates. Increased angulation of screws were found to be trending towards an association with an increased RF rate. We did not, however, find an association between increased stiffness of a rod (ie, rod diameter and/or rod material) and lower RF rates.

To the authors knowledge, this is the first study to examine orientation and spatial position of screws adjacent to a 3CO site. This was only possible by rigorous analysis of calibrated standing full length scoliosis radiographs. With these calibrated radiographs we were able to build a software program to examine how screw position impacted RF rates. There are several studies that examined instrumentation failure around a 3CO site. Kavadi et al[18] examined 26 patients that underwent a 3CO and found that 25 of these patients had bilateral pedicle screws two levels above and below the 3CO site. Jager and colleagues examined rod configuration around a 3CO site and found that double rod and bridging-rod constructs were more resistant to fatigue failure as compared with single rod constructs. There was, however, no analysis done regarding fixation points surrounding a 3CO site. Barton et al[19] did examine screws in relation to RF rates, but found that screw density did not impact RF rate. Our analysis demonstrates that surgeons may be able to reduce RF rates by strategic placement of screws around a 3CO site. Specifically, placement of screws with increased working length and less angulation around a 3CO site may better protect the rods. We hypothesize that increased working length of screws around a 3CO site allows for more optimal stress distribution along the rod. Further biomechanical research is required to validate this. The authors also acknowledge that anatomic factors such as angulation of adjacent pedicles likely heavily influences the ability of a surgeon to determine adjacent screw placement.

The concept of rod configuration and our definition of "multiplanar" rod placement is related. Gupta et al[20] have shown that use of satellite rods is associated with lower rates of RF. A satellite rod is independently anchored in pedicle screws within a larger construct surrounding a 3CO site. In the context of AO principles, a satellite rod would be defined as a "multiplanar" rod construct. We used a satellite rod to illustrate our concept of a "multiplanar' rod construct in Figure 3. Our finding that there is a lower RF rate associated with multiplanar rod constructs fits with this previously published work. It is also consistent with the basic architectural concept of load distribution as is created with use of an "A" frame when building a roof. We would encourage further biomechanical research on the different stresses/strains applied to the rod-implant system based on these different rod configurations.

Given the constraints of pedicle screw design we were also not surprised to find that the distance between osteotomy site and rod was not different between the RF and non-RF cohorts. This likely stems from the fact that rods must fit on to a tulip head within a pedicle screw and surgeons cannot greatly impact this relationship. Therefore, the distance between the rod and osteotomy site is consistent no matter the procedure.

The benefits of multirod constructs have been shown in the literature, but this study is the first to examine specifically the influence of placement of rods in multiple planes on RF rates. Both clinical and biomechanical studies have shown the benefits of using more than 2 rods at a 3CO site.[11,21–24] Our analysis shows that multiplanar placement of rods around a 3CO site may better resist torsional forces surrounding an osteotomy site.[25,26] Furthermore, this result fits with previously published results showing how accessory/satellite rods assist in lowering RF rates.[27,28] The authors acknowledge that there may be times when a surgeon would need to use a smaller working length and/or larger angle between adjacent screws at a 3CO site to achieve correction. In this situation a surgeon may want to further agument their construct with additional rods and/or rods at different angles.

We found no difference in RF rates based on rod diameter or material, which is consistent with previously published reports. Hellman et al[29] found no statistically significant difference in RF rates between stainless steel and cobalt-chrome rods. Smith et al[10] found that cobalt-chrome rods were associated with higher RF rates as compared with stainless steel or titanium alloy rods on univariate analysis. Contrastingly, Han et al[30] found lower rates of RF associated with use of cobalt-chrome rods. Given these varied findings it is not surprising that we were unable to find a significant difference in RF rates associated with rod stiffness as defined by rod material and/or rod diameter.

We found that interbody use trended towards having a protective effect on RF rate. The biomechanical theory behind interbody use is that it provides anterior column support for the inherently destabilizing 3CO procedure. Hallager et al[27] used a cadaveric model to show how an interbody offload the primary rod crossing a 3CO site. Similarly, Deviren et al[31] used another cadaveric model to demonstrate the stabilizing effect of an interbody at a 3CO site. Interbody use may assist in creating a solid construct around a 3CO site, but our data does not definitively establish this link. This is likely because of the fact that our analysis was underpowered to properly assess this impact.

There are several important limitations to our study. The problem of RF associated with a 3CO is likely multifactorial. We did not examine how such things as bone health, bone graft choice, patient medical comorbidities, activity level before or after the procedure or a myriad of other factors might impact on RF within our analysis. All of these factors and likely more impact when and why a patient develops instrumentation failure and RF. We did aim, however, to determine whether a portion of AO principles for external fixation could be applied to a 3CO site, which we were able to show. Given the retrospective nature of this study we could not control for surgeon/surgery specific decision making. Some conclusions, such as rod diameter/rod material may be influenced by a surgeon trying to create a stiffer construct in a clinical situation where he/she may be more concerned about a RF. The RF rate may differ between groups with the passage of time that is not highlighted in this study. For instance, we did not examine whether the change in overall alignment/lumbar lordosis impacted the study's conclusion. This is only early follow up for a RF study and results may change based on longer term follow up. Our data was also derived from a surgeon maintained database and we have no way of determining external validity of the data. Furthermore, we do not have a control group to confirm the accuracy of our conclusions. The authors also acknowledge that a portion of the factors examined may not modifiable by the surgeons such as the working length of adjacent pedicle screws or the rod to screw distance. Finally, the overall sample size of our 3CO cohort is small and we acknowledge that we do not have enough statistical power to determine certain factors related to RF.

In conclusion, our study shows that surgeons can incorporate a portion of AO principles traditionally used for external fixators when designing a preoperative plan for a 3CO procedure. Long bone fractures and 3CO sites are both challenging biomechanical environments that require solid instrumentation constructs to allow for proper bone union. Placing more rods around a 3CO site, placing rods in multiple planes around a 3CO site, placing adjacent screws with a larger working length around the 3CO site and with less angulation was associated with lower early RF rates. We hope these findings assist surgeons in preoperative planning when performing a 3CO for ASD.

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