Scoliosis Round Table:

What are Your Optimal Surgical Strategies for a Double Major Curve in Adolescent Idiopathic Scoliosis?

Matthew E. Oetgen, MD, MBA[1]; Stuart L. Weinstein, MD[2]; Lindsay Andras, MD[3]; Suken Shah, MD[4]; Daniel J. Sucato, MD, MS[5]

[1]George Washington University School of Medicine, Washington DC; [2]University of Iowa Hospitals and Clinics, Iowa City, Iowa; Keck School of Medicine, University of Southern California, Children's Orthopaedic Center, Children's Hospital Los Angeles, Los Angeles, CA; Nemours/Alfred I duPont Hospital for Children, Wilmington, DE; Texas Scottish Rite Hospital, University of Texas Southwestern Medical Center, Dallas, TX

Introduction

Adolescent idiopathic scoliosis (AIS) is a common condition seen by pediatric orthopaedic surgeons. While the general indications for surgical treatment have changed very little over the past few decades, the methodology has. This is due to a greater understanding of the biomechanics, advances in surgical technique and instrumentation, and a more robust understanding of the goals and outcomes of surgical intervention.

When surgical intervention is indicated, posterior spinal fusion remains the gold standard for the treatment of adolescent idiopathic scoliosis with the aims:

1. Correction of deformity while maintaining good coronal and sagittal balance with as much flexibility as possible.
2. Fusion of the spine to prevent future deformity progression in a safe, complication free process.

Despite these relatively simple objectives, the optimal technique to achieve these goals is hard to define. Different strategies exist for preoperative planning, instrumentation, and deformity correction.

Additionally, while understanding that the technique of deformity correction is important, recent investigations into achieving maximum quality and safety in AIS surgery have shown standardization of the care pathway is likely of equal importance in achieving the best outcomes for patients.[1-3] Yet one technique may not be optimal for all types of deformity correction and selective implementation of different methods defines the "art" of surgery.

The discussion and sharing of differences in surgical planning, approach, and technique by experts is a powerful way to learn new insights into methods of treatment. The goal of this roundtable is to present a case of a patient with AIS and to discuss different surgical approaches from a group of experts and to learn from their experience in treating AIS.*

**This report summarizes key points from each panel member, and where similar concepts were discussed by multiple panel members, this is noted. A complete transcript of these valuable pearls and pitfalls are provided in Appendix 1. This discussion is extremely thorough and valuable for those desiring a nuanced description.*

Invited Experts

Stuart L. Weinstein, MD
Ignacio V. Ponseti Chair and Professor of Orthopaedic Surgery/Professor of Pediatrics, University of Iowa Hospitals and Clinics, Iowa City, Iowa

Lindsay Andras, MD
Assistant Professor of Orthopaedic Surgery Keck School of Medicine, University of Southern California Children's Orthopaedic Center, Children's Hospital Los Angeles, Los Angeles, CA

Suken Shah, MD
Division Chief, Spine and Scoliosis Center, Clinical Fellowship Director, Nemours/Alfred I duPont Hospital for Children, Wilmington, DE

Daniel J. Sucato, MD, MS
Chief of Staff, Texas Scottish Rite Hospital Professor, Department of Orthopaedic Surgery, University of Texas Southwestern Medical Center, Dallas, TX

Case

13+9-year-old girl who is 4 months post-menarchal who presents for a second opinion regarding her spinal deformity. She was originally diagnosed at age 11 with a right thoracic deformity of 29° and a left thoracolumbar deformity of 21°. She was noncompliant with a brace and now presents with progression of her deformity. Current radiographs show an upper left thoracic curve of 26° that bends to 22°, 62° right thoracic that bends to 40°, and 55° left lumbar curve that bends to 29°. She is a Risser 2. (Figures 1-2)

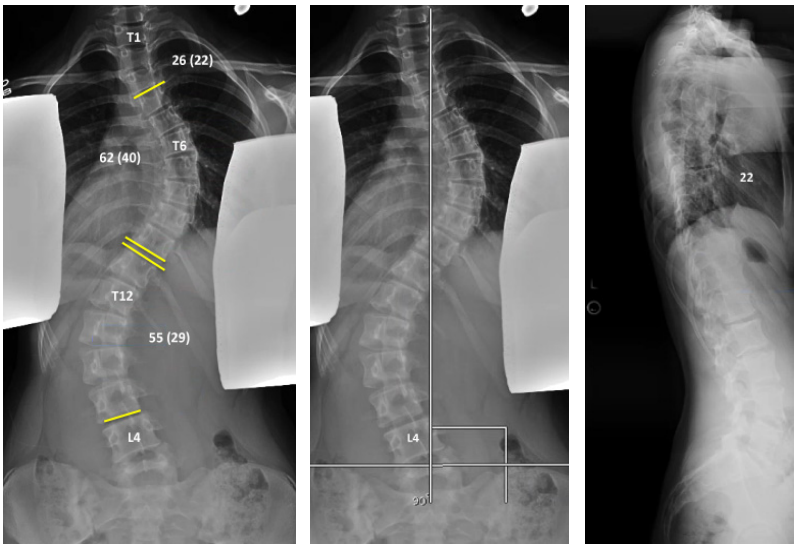

Figure 1a, 1b and 1c. *Presenting PA and Lateral Radiographs*

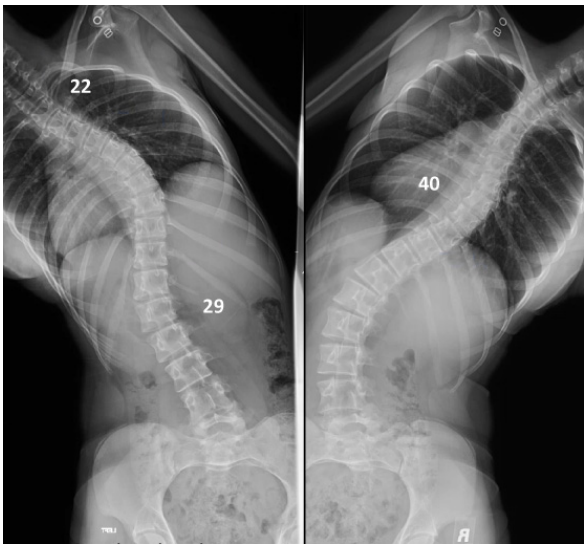

Figure 2. *Unbending Films*

Case Questions and Panel Discussion

1. Has this child met indications for surgical treatment?

Drs. Shah and Sucato summarize the consensus from the panel.

SS: *Yes. She has progressive scoliosis >50 degrees, is skeletally immature, and is mildly symptomatic.*

DS: *Yes. The absolute indications for surgery in AIS are those patients whose curve will continue to progress despite skeletal maturity. This generally means thoracic curves greater than 50 degrees and thoracolumbar/lumbar curves greater than 40 or 45 degrees. For the case presented here, the risk for curve progression is exceptionally high, and surgery is indicated.*

2. How would you approach this patient in terms of a preoperative evaluation?

All our panel members have a similar basic approach to preop evaluation as summarized by Dr. Weinstein.

SW: *Our preoperative workup would include a complete physical examination and blood work, as well as a type and screen. Patients are given the opportunity to complete standardized health-related quality of life (HRQOL) surveys prior to their initial visit to our service, either through our online patient portal or during the check-in process.*

LA: *I agree but would add that for curves over 70 degrees, they have a cardiology evaluation/echo to evaluate for pulmonary hypertension and a pulmonary evaluation, which includes PFTs. Patients with significant preoperative pain concerns are referred to psychology or our pain team. (This pain and psychological evaluation are described in the Appendix by Dr. Sucato.)*

3. What type of preoperative imaging do you typically obtain?

All our panel members agree that MRIs are not routinely obtained. Instead, they are reserved for specific indications such as: neurological findings, kyphosis at the apex, atypical curve, pain, rapid progression, early onset, and left sided curve (SS).

All our panel members have similar thoughts on what images to obtain as Dr. Sucato writes.

DS: *All surgical patients get an AP and lateral radiograph using the EOS technology to decrease the amount of radiation as well as to have the potential to measure the three-dimensional deformity. Two-view supine best-bend radiographs are also obtained and are used to help classify the patient using the Lenke classification which ultimately predicts those curves, which potentially should be included in the fusion.*[8]

LA: *I agree, but we have noted if it doesn't look as flexible on XR as what you appreciate clinically, then consider assisting on a repeat film.*

SS: *I would add traction/pull films for all curves ≥ 80 degrees. I would like to do all imaging in the EOS, but I'm not convinced erect benders give you a reliable picture.*

4. How do you classify these deformities, and how do you use this classification to begin your surgical planning?

All our panel members use the Lenke System with some caveats.

LA: *The Lenke classification remains the preeminent classification system both in our practice and worldwide. I think some of the work on 3D modeling and classification is exciting but not quite to where I am using it in everyday practice.*[12]

DS: *AIS curves that are indicated for surgical treatment should be assessed using the Lenke classification. Ultimately, the radiographic classification of each patient needs to be reconciled with the physical examination of the patient to ensure that the appropriate curves are included in the fusion. In general, it is important to look for opportunities to preserve motion segments since the long-term health of the spine is dependent in general, on two aspects: balance and motion.*

5. How do you do your surgical planning for this type of surgery?

Our panel emphasizes the importance of sagittal plane assessment, shoulder balance on radiographs and physical examination, and preservation of lumbar motion.

SW: *I start by looking at the sagittal plane to determine whether the patient has hypokyphosis and what I ideally would like to achieve in sagittal plane correction or restoration. On both the standing PA and supine AP, I identify a perpendicular to the sacrum to identify the center sacral line to determine the touched, substantially touched, neutral, and end vertebra. I next draw a line connecting the superior aspects of the acromion to get an idea of shoulder tilt and also the angle of the T1 superior endplate and superior aspect of the first ribs. I do the same measurements on the supine film. My goals of surgery are to level the shoulders, correct as much of the rotational deformity as possible, and balance the spine both in the coronal and sagittal plane. Distally, my goal is to spare as many lumbar segments as possible in achieving correction and balance.*

LA: *"Start with the lateral" has been a mantra at our institution. This way, you make sure you don't forget to consider it. For me, this has three components:*

1. Check for spondylolysis/spondylolisthesis, which can be seen in 10-15% of AIS patients.

2. Look at the sagittal profile and determine if that makes any of the minor curves structural (this is one of the points of the Lenke classification that people sometimes forget to pay attention to; for example, if the T2 to T5 kyphosis is more than 20 degrees then the proximal thoracic curve is structural and you will develop imbalance if you don't include it).

3. I draw the posterior sacral vertical line to determine the stable sagittal vertebra line and know I shouldn't plan to end my construct at a more proximal vertebral body based on the PA radiographs.

Then I switch over to the PA and bending views. From these, we can determine that both the main thoracic (major) and lumbar curves are structural (this should also coincide with our clinical exam), but the upper thoracic is not (bends out to less than 25), so from that I conclude that I would include both main thoracic and lumbar curves. Since the upper thoracic curve is not structural, then I usually go by T4 for high right shoulder (which this is by clinical description though it is subtle on radiographs), T3 for level shoulders, T2 if the left is high. For the LIV, typically, you would use the vertebrae just touched by the center sacral line, but this is one area where we frequently "break the rules" and especially with L3 vs. L4. We will "work hard" to end at L3 and may have some significant potential benefit from doing that.

SS: *I start with a detailed exam of the radiograph, with special attention to the lateral and 3D views reproduced using the EOS system. The areas I concentrate on are the rib hump offset, the need for thoracic kyphosis correction, and preservation of lumbar lordosis based on radiographic pelvic incidence. Once that is done, make sure you compare the radiographic deformity and that of the patient's clinical appearance (often photos of the patient from the clinic are helpful). I then determine the UIV based on the shoulder appearance. Similar to Dr. Andras, I include T3 if a large main thoracic correction is planned. I try to pick the LIV as the last*

touched by center sacral vertical line (LTCSVL), but almost never to L4.

DS: *The initial steps to surgical planning are first to determine which curves require inclusion in the arthrodesis and then to decide which specific vertebral levels to instrument and fuse. The physical examination is the most important aspect of determining which curves require surgical treatment and includes an assessment of shoulder elevation, coronal balance, rotational deformity of the potential curves, and waistline asymmetry. The radiographs should then be assessed, and a comparison of these images to the physical appearance of the patient is then made. In general, the physical examination of the patient supersedes the radiographs if there are any discrepancies noted. For example, if the left shoulder is elevated despite the radiographs not demonstrating a structural PT curve (because the curve bends to less than 25 degrees), it is important to include the PT curve to ensure that shoulder balance will be achieved following surgery.*

6. How do you determine the need for osteotomies, and how do you decide where to place these if needed?

SW: *I do complete inferior facet joint excision, remove the spinous processes to the level of my inferior facet excision, and thin the ligamentum flavum significantly at each level to allow maximal mobility. If, however, the curve is extremely rigid or very large (greater than 75 degrees), then I consider using osteotomies. Ponte osteotomies add to the potential blood loss and hematoma formation and the increased risk of neurologic deficit, so hence, I do them when necessary but not routinely.*

LA: *For me, the debate of whether or not to do Ponte osteotomies is a "when and how" not "if" question.*

SS: *Always, as the principle is to mobilize the spine. (Drs. Andras and Shah use ultrasonic bone scalpel for facetectomies and Pontes to limit blood loss.)* [23]

DS: *The use of posterior column (Ponte) osteotomies in AIS is somewhat controversial and, in general, I employ the same strategy as screws in that they are only necessary to properly dose the amount of correction needed for the deformity.*

7. How do you optimize patient positioning in the OR to help with correction?

SW: *The key for me is to position the patient in a way that promotes normal standing posture. This helps me ensure that I have good coronal and sagittal balance and that my films are taken in the appropriate position.*

DS: *The hip pads should be at the level of the anterior superior iliac spine, and I most often place them more distal, especially for those patients in which we are instrumenting into the lumbar spine. In this way, the hips can be extended to improve lumbar lordosis when more is desired.*

SS: *We use cranial tongs for bigger curves and traction when necessary. I will adjust the chest pad to aid with thoracic kyphosis restoration, sometimes even adjusting intraoperatively before rods go in. (Dr. Andras describes a similar approach to positioning.)*

8. What are your tips and tricks for blood management in the operating room?

Drs. Andras, Shah, and Sucato employ controlled hypotensive protocols of 60 mmHg for exposure, ~75 mmHg for correction through completion.

SW: *Over the years, I have gone away from using any hypotensive anesthesia and currently just keep the patient's normotensive, normothermic, and rely on meticulous surgical dissection techniques and as short as possible surgical times to prevent blood loss. We use tranexamic acid (TXA) preoperatively with a 50 mg/kg bolus and then 10 mg/kg continuous infusion until the wound is closed and dressings were applied.*[22] *(Drs. Andras and Shah also note TXA, SS with 30mg/kg bolus and a 10mg/kg infusion.) I have not used the cell saver in over 25 years.*

SS: *Cell saver is used for all cases except anterior and selective thoracic fusions.*

9. What is your standard deformity reduction technique for this type of deformity?

Our panel emphasizes the importance of differential rod bending as described by Dr. Weinstein and the use of pedicle screw derotation described by Drs. Andras and Sucato.

SW: *I would be placing the left-sided rod first, contouring the rod as I would like to see it in the sagittal plane, restoring kyphosis in the thoracic spine. I would be capturing the rod at every level that is instrumented. I would first derotate the lumbar spine with the uniplanar screws, which I use in this region. I then would put multiple screwdrivers in the apical thoracic vertebrae screwheads and derotate the spine and use the reduction screws on the concave side to help derotate the spine and pull the spine to the rod to create additional kyphosis in the thoracic spine. In the right-sided rod, I tend to contour the thoracic spine with minimal kyphosis as I tend to use this rod to "push down" and derotate the ribs on the curve convexity. Similarly, I bend the lumbar segment a bit less with lordosis to help derotate the lumbar spine further. Once the main thoracic and lumbar curves are stabilized, I do my shoulder leveling by distraction across T3 on the left with a T2 hook loosened to allow me to push up on the left shoulder. Then I distract at T2 on the right relying on ligamentotaxis to balance the shoulder on that side. Finally, I compress the T2-3 "claw" on the left to secure these hooks. I check balance with the fluoroscopy looking for horizontalization of all the cervical vertebrae and the upper thoracic vertebrae, and then I check with fluoroscopy distally looking for horizontalization of the distal portion of the spine.*

LA: *In addition to aggressive differential rod bend techniques and vertebral column rotation at the apex of the thoracic and lumbar curves, I follow that by fine-tuning with compression and distraction to balance the UIV and LIV.*

SS: *With differential rod bending, only one set screw is tightened to keep the rod properly oriented in the sagittal plane while the other rod is implanted. Then, set screws are tightened segmentally as axial plane is corrected via segmental direct vertebral rotation. I also work hard to balance the LIV with compression/distraction while simultaneously de-rotating the LIV to neutral if it is not spontaneously so. Look at LIV+1 – does it look perfect? If not, it won't look any better when she stands up, so get it right in the OR!*

DS: *I prefer to start this process by placing derotators on the convex side of the lumbar spine to correct and derotate the lumbar curve followed by a temporary right-sided lumbar rod. Now the lumbar curve is partially corrected, and the left rod can be placed engaging the rod partially in the left lumbar spine while engaging only the top screw(s) of the thoracic curve leaving the overcontoured rod posterior to the apex of the thoracic spine. The temporary right lumbar rod is removed, and correction of the spine using the left rod begins with the apex of the thoracic curve pulled to the rod with reducers and the lumbar curve corrected as partial rod rotation to complete the axial plane correction. In-situ bending of the rods in the coronal plane provides opportunities to improve correction and generally are performed at the apex and prior to compression-distraction maneuvers.*

10. How do you judge your correction in the operating room?

SW: *I judge my correction through intraoperative fluoroscopy as mentioned above, or on occasion 72-inch films taken in the operating room, but again, I find this rarely necessary. I make my decisions about whether I need to do more or less well before this point in the surgery. I make continual assessments along the way, never at the end. I may take a quick fluoroscopic view if I have any concerns.*

LA: *We have a T-square that I center first on the hips to make sure the upper portion is traveling through the center of T2, so I know coronal balance has been achieved.*[27] *Then I flip it around and center it on the coracoid processes to judge the shoulder balance.*

DS: *Every spine deformity surgery at our institution has a 3-foot film obtained from an overhead-mounted X-ray machine in the OR.*

11. What is your immediate postoperative patient protocol?

Our panel has worked to develop institutional rapid recovery protocols that get patients home 2-4 days postoperatively (Please note the CHLA Intrathecal Injection Technique in this edition of *JPOSNA*).

SS: *We were among the first to use gabapentin and Toradol to decrease morphine equivalents, so we have lots of experience with rapid recovery pathway.*[28] *Now, on top of that, we use a clonidine patch, get on oral pain medicine on POD 1 with oxycodone, Tylenol, and valium. The patient sits up in bed in PACU and typically is admitted to the floor the first night, with something to drink. To advance mobility, we expect the patient to be out of bed to the chair twice on POD 1 and walk in the hall on POD 2, with stairs should be cleared by the end of POD 2 or 3. With this protocol, we have been able to achieve an average length of stay of 2.7 days.*

DS: *Our patients have an epidural catheter placed at the time of surgery with administration of rupivicaine, together with continuous intravenous dexmedetomidine (Precedex®) without narcotics except for Dilaudid prn. The patient is given oral meds and, if tolerated, the epidural is removed at 11 am, together with the arterial line and Foley catheter. The patient is in a chair for 1 hour, back to bed, and then up walking laps 2 hours later. Walking is done three times per day, and in patients with a thoracic fusion, only the patient is usually discharged the second postoperative day. If the fusion extends into the lumbar spine, the patient is usually discharged on POD 2 or 3.*

Figure 3. *Postoperative radiographs of T4 to L3 reveal excellent sagittal and coronal balance with level shoulders and a horizontal LIV within the stable zone.*

12. What is your longer-term activity protocol?

SW: *We release them to full unrestricted activities at 6 months postop. For male patients I generally do not recommend tackle football or competitive wrestling (no data to support these restrictions just my intuitive feeling of too much risk).*

LA: *We agree that there is likely some increased risk of spine injury with participation in contact sports. In the absence of level 1 data on this subject, we all have to share that theoretical risk and balance it against the known benefits of sports participation.*

DS: *We restrict contact sports for 6 months for any fusion into the lumbar spine. For our selective thoracic fusions, we allow full activities without restrictions at 6 weeks. Patients are seen back at 1 year from surgery unless there are concerns by the family.*

Conclusion

As can be appreciated by the panel discussion, many different successful techniques exist for performing posterior spinal fusion for AIS. While differences exist in the details (the need for osteotomies, implant density, implant type, reduction maneuver, even follow up imaging and schedules), what can be appreciated in the comments of all of these experts is that the goals of spinal balance, achieving a lasting fusion, and avoiding complications during and after surgery are universal. Detailed preoperative planning, meticulous surgical technique, and open and honest communication with families, are the keys to success in pediatric spinal deformity surgery.

The panel provides their Keys to Success

Dr. Weinstein

1. **Loosen the spine.** I always do complete facetectomy in the lumbar spine and 90% removal of the inferior facet in the thoracic spine. I also remove the spinous process back to the level of resection of the inferior facet in addition to thinning the ligamentum flavum with my "fluted" Midus Rex burr to get as much mobility between segmental levels.

2. **Maximize screw size.** I try and use the largest pedicle screw size that I think the patient can tolerate, as I believe this gives better control during correction of the deformity.

3. **Be flexible with your implant plan.** I tend not to spend too much time trying to cannulate pedicles, which are extremely small and thin. As I do all my screw placement by the freehand technique, if I cannot penetrate and cannulate the pedicle quickly, then I tend to skip it and move to the next level proximally. I also, as mentioned above, place my screws distal to proximal always thinking about "plan B" so I am very cognizant of the fact by viewing the preoperative X-rays how I can accomplish my ultimate goals if I can't get a pedicle screw in place, how I can use an occasional hook or even go back to a more "ancient technique" called the three-rod technique popular for big curves in the Cotrel-Dubousset days. I think it is very important in children for spine surgery to be facile with the use of corrective techniques e.g. using hooks as a fall back for some uncomfortable situations. I never plan to extend my levels because of blown pedicles so particular care must be taken with screws distally.

4. **Shoulder balance is key.** I think it is critical for all pediatric spinal deformity surgeons to develop techniques and have an understanding of the spine such that one is always able to achieve shoulder balance. Shoulder imbalance is, in my experience, the one deformity that patients and families are most unhappy about, much more so than residual rib prominence.

5. **Know your implant system.** Each of the implant companies patent their tools and implants. Rods and screws vary from company to company, and just because you are an expert with one system does not mean you can rapidly gain that expertise using another company's system. Rods may have different modulus of elasticity, even within the same company. Screws have different thread pitches, and different pull out strengths, and patients are different with respect to bone quality.

Dr. Andras

1. **Keep your team informed.** Email your team the week/weekend before and include your surgical plan for levels, implants, and any other equipment needed, as well as any pertinent information about the patient (i.e. MRI negative for intraspinal pathology, no pulmonary hypertension on echo).

2. **Think power.** Power pedicle screw placement (and tract preparation) is really helpful for both patient and surgeon preservation.

3. **Spread the force.** Aggressive differential rod bend and lots of serial reducers to share the load.

4. **Avoid "shoulder shame".** No one is happy with a high left shoulder (patients, parents or surgeons). Understand this has become much more prevalent now that we have more powerful corrections and more rigid fixation. Focus on getting this right in the operating room.

5. **Develop a preoperative class.** Work with your hospital, nursing staff, and child life to develop a preop class that allows patients and parents to raise their concerns without worrying about how it will be perceived by their surgeon. I think it really helps patients and families prepare for the upcoming surgery.

Dr. Shah

1. **Proper preop planning.** Deliberately classify *EVERY* curve, look for proximal thoracic kyphosis, thoracic lordosis and seek to match pelvic incidence with lumbar lordosis and thoracic kyphosis (better neck alignment also). Make sure to look for rib/vertebra numbering anomalies and the Lenke 1 subtypes (1AR, 1AL) to avoid making mistakes that will lead to adding on.

2. **Manage patient/family expectations.** Frankly discuss complications but frame them in the proper way that families understand (severity, odds ratio, plan of action for treatment).

3. **Maximize available technology.** Bone scalpel for facetectomies and osteotomies reduces blood loss, poly-directional reduction screws placed proximally and built-in retractor where soft tissue preservation is key, differential rod contouring for severe curves, and sublaminar bands at the apex for translation in patients with poor bone avoids screw pullout.

4. **Optimize your bone graft.** Bone marrow aspiration prior to screw insertion gives stem cells, growth factors, and nutrients that make osteoconductive bone grafts (allograft and synthetics) osteoinductive.

5. **Develop a team** - OR teams for spine surgery improve efficiency and outcomes.

Dr. Sucato

1. **Share the plan.** Share the preoperative plan with the entire operative team, including the anesthesia team, the scrub tech, circulating nurse, spinal cord monitoring team, and assistant surgeon (fellow or resident). This gets everyone on the same page, provides opportunities for discussion, and makes everyone feel part of the operative team.

2. **Be efficient.** This includes doing as much as you can with the instrument in your hand, transitioning between steps in as seamless a way as possible and always communicating with the operative team members to anticipate the upcoming steps.

3. **Be at your best physically and mentally.** There is a physical and emotional aspect to these surgeries, and you need to be ready to perform at a high level.

4. **Understand intraoperative neuromonitoring.** I would recommend you have the team set up a monitor so you can see the waveforms and recognize the subtle changes that are occurring in real time–a pattern recognition process that provides an improved and more rapid response to IONM changes when they occur.

5. **Stay until the completion of the surgery and debrief.** The closure may be as important to avoiding complications as anything that we do. It also demonstrates your commitment to the patient, to the team, and gives you time to solidify relationships with your valuable team members. Provide an opportunity for a good debrief to highlight things done well and where there are opportunities. I have never seen a perfect operation, and the operative team will benefit, and ultimately, the patient will benefit from this "deliberate learning."

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Appendix 1

Case Questions and Panel Discussion

1. Indications for surgery?

SW: The indications for surgery in this patient include progression of her curvature to 62 degrees from the initial curve of 29 degrees and not having reached skeletal maturity. She is currently Risser 2 and only 4 months post-monarchal. Firstly, I want to comment on her initial treatment. She was first seen at 11 years, premenarchal, with a right thoracic curve was 29 degrees and a left thoracolumbar curve was 21 degrees. In my clinic I place great reliance on digital skeletal age for prognostication as I feel it is much more accurate in assessing maturity than the Risser sign. In addition, even though she was premenarchal at that stage and no doubt Risser 0, I would also like to know what her triradiate cartilage status was (open or closed) as another indicator of maturity. In our clinic we usually use a patient decision aid (https://uichildrens.org/ais-prognosis-calculator-simplified) to discuss prognosis with the patient and their family.[4] We know from the Braist clinical trial that bracing is effective in preventing the need for surgery and high-risk patients with AIS.[5] The use of the brace for only 10 hours a day would not be sufficient to get the optimal benefit of the orthotic. Not that bracing works in every case but effective treatment would mandate much greater wear; 18 hours a day per the Braist trial.

LA: In a patient whose thoracic major curve has exceeded 50 degrees such as this, the natural history studies predict continued progression even after skeletal maturity. Consequently, even in the asymptomatic patient with a 60-degree curve in adolescence, I would recommend surgical intervention. We know that addressing this as a teenager is a far better option than addressing the deformity as an adult later in life.

SS: Progressive scoliosis >50 degrees, skeletally immature female and mildly symptomatic.

DS: The indications for surgery in AIS should take into account the clinical appearance and radiographic analysis of the patient as well as their perception and the parent's perception of deformity. The absolute indications for surgery in AIS are those patients whose curve will continue to progress despite skeletal maturity. This generally means thoracic curves greater than 50 degrees and thoracolumbar/lumbar curves greater than 40 or 45 degrees. There are additional factors that go into deciding whether surgery is indicated and that especially includes coronal/trunk balance. For example, a well-balanced double curve in a skeletally mature patient whose magnitudes are 50 degrees and would include fusion to L4 may be someone that can be observed over time since the procedure is most likely going to limit some mobility and may not progress with time and the functional outcome of the patient may be better without surgery. On the other hand, a 45-degree "single overhang" thoracic curve with a 3cm trunk shift is better off having surgical treatment to normalize the balance and improve the cosmetic appearance of the patient. For the case presented here, with the largest curve being 62 degrees, while still Risser 2, the risk for curve progression is exceptionally high and surgery is indicated. In this particular case, significant curve progression of the lumbar curve would place at risk the ability to stop at L3 and the need to go to L4 with time, this is something to consider and provides more reason to move forward with surgery.

2. How would you approach this patient in terms of a preoperative evaluation?

SW: Our preoperative work up would include a complete physical examination, blood work to include a type and screen and CBC w/diff, PT/INR, PTT, Sodium, Potassium, Chloride, CO2, BUN, Creatinine, Glucose, Urine Analysis, Type and Screen (we also do an Albumin if neuromuscular and a pregnancy screen if patient is over 11 years of age). Our clinic system has

automated patient data entry of standard patient reported outcomes (PRO) forms. Patients are given the opportunity to complete standardized health related quality of life (HRQOL) surveys prior to their initial visit to our service, either through our online patient portal or during the check-in process. These include: PROMIS Health and Function and SRS-30 (at baseline and 1 year postop). If the patient has a very thin body habitus or very low BMI, we might consider nutritional evaluation and possibly some preop nutritional counseling but would certainly discuss the symptoms of Superior Mesenteric Artery Syndrome with the patient and family preoperatively and in the pre-discharge discussions.

LA: Our current protocol is CBC, Chem 8 and coags in addition to a type and cross for two units. However, we are currently in the process of evaluating whether that is necessary as it seems to be pretty low yield and some other centers are considering eliminating this as well. Although we order a preoperative nutrition evaluation on all of our early onset and neuromuscular patients, we have not typically done that for idiopathic patients unless there was a markedly low or high BMI that would potentially increase risk of surgical complications. For otherwise healthy adolescents with curves less than 70 degrees, we do not routinely order any additional medical evaluation. For curves over 70 degrees, they have an cardiology evaluation/echo to evaluate for pulmonary hypertension and a pulmonary evaluation which includes PFTs. Patients with significant preoperative pain concerns are referred to psychology or our pain team, having them meet those physicians preoperatively and establish a relationship I think is really beneficial. In terms of PRO, we are using the SRS-22.

SS: We obtain a preop CBC and type and screen only after screening questions for bleeding disorders and anesthesia/surgical issues in family. A nutrition evaluation is obtained only if the BMI indicates the patient is significantly underweight. We use the SRS questionnaire for preop PRO.

DS: The preoperative evaluation is critically important for any patient undergoing surgery and that is certainly true for patients with AIS. We should never forget the basics of obtaining a good history and performing a very good physical examination. Any history of cardiac or respiratory issues should be evaluated by those specific specialties. We perform a risk assessment questionnaire including personal history of bleeding disorders as well as any history of a family history of these conditions. A nutritional assessment is performed when the patient has a low BMI (<18cm2/kg) or high (>85 percentile) as these are associated with a significant risk of complications including infection and poor wound healing. At the time of admission, electrolytes are also drawn. For the underweight patient, they get a CBC with differential, albumin, prealbumin, iron profile and a Vitamin D-25 hydroxy. For the overweight patient, they get the same with an additional hemoglobin A1c and liver function tests. For all other patients (80%) who have normal weight and are healthy, the only lab that is drawn is a CBC. We have recently demonstrated that the risk of receiving a blood transfusion(s) in our AIS patients are: lower BMI percentile (48% vs 61%), larger preoperative curve (69° vs 61°), lower preop hemoglobin (13.1 vs 13.7), use of osteotomies (Ponte), greater fusion levels (11.8 vs 10.3). So, for patients with an average BMIT (and therefore, larger blood volume) with a single thoracic curve in the 50-degree range in which osteotomies are not performed the likelihood for intraoperative or postoperatrive blood transfusions is small. Postoperatively, a single CBC is ordered on POD 1 and if the hemogloblin is greater than 9.6 mg/dl the likelihood of transfusion during the hospital stay is very low and a repeat CBC on POD 2 is not ordered.[6] In this adolescent age group, a low threshold should be utilized for an evaluation by a psychologist or counselor to assess their “readiness” for surgery, including any excess stressors in their life, their interest in carrying out the postoperative activities necessary for success, their expectations with respect to outcome, etc. In a recent study, postoperative pain following AIS surgery was predicted by preoperative assessment of anxiety and

perioperative pain. In a large series of AIS patients, mental health preoperatively predicted postoperative mental health and also predicted self-image scores at 2 years.[7] We use a number of patient-reported outcome scores to assess for these issues.

3. What type of preoperative imaging do you typically obtain?

SW: Our preoperative imaging needs may be altered should the patient have any unusual features such as atypical curve pattern, an unusual amount of pain (takes patient out of pleasurable activities, frequent school absences, pain that awakens from sleep, etc.) neurologic deficit (particularly asymmetrical abdominal reflex), or if their history included the onset of the curvature under 10 years of age. In these circumstances we generally order a preoperative MRI. What is often not discussed is the sagittal plane. If the patient with assumed AIS has a kyphotic thoracic spine, then that too would be unusual and warrant a preoperative MRI. With respect to radiographs, our standard preoperative films include a standing PA, standing lateral (done in the EOS machine) a supine AP and supine maximum right and left side bending films. Over the last several years I have placed great reliability on determination of instrumentation levels by comparing the standing PA to the supine AP films augmented by the side bending films. Side bending films are notoriously unreliable and I have done them in many ways including standing, sitting, and fulcrum bending. In our clinic there are too many variabilities including patient effort and technician proficiency in positioning patients positioning bolsters, so I have been very comfortable over the last several years in making decisions based on the aforementioned films. In neuromuscular patients, we do use traction films.

LA: We are not routinely ordering MRI scans on idiopathic patients preoperatively. However, it is worth noting that "idiopathic" is a diagnosis of exclusion and a thorough history and physical exam is a prerequisite of reaching that conclusion.

For most idiopathic curves we do supine bending films. There can be some variability with their accuracy based on patient effort/skill of the radiology technician. If it doesn't look as flexible on XR as what you appreciate clinically, then consider assisting on a repeat film. This is particularly true when clinically the lumbar curve is minimal on Adams forward bending and the bending film measurements are borderline, its worth taking a few more minutes and another film to see if they are candidates for a selective thoracic fusion.

SS: We do not routinely obtain MRIs for AIS, but the indications for this would be neurological findings, kyphosis at the apex, atypical curve, pain, rapid progression, early onset, and left-sided curve. The preoperative bending radiographs we obtain are fulcrum benders over apex thoracic curve and supine left bender for lumbar curve. We get traction/pull films for all curves ≥ 80 degrees. I would like to do all imaging in the EOS, but I'm not convinced erect benders give you a reliable picture.

DS: All surgical patients get an AP and lateral radiograph using the EOS technology to decrease the amount of radiation as well as to have the potential to measure the three-dimensional deformity. Supine best-bend radiographs are also obtained, one to the right and one to the left, and are used to help classify the patient using the Lenke classification which ultimately predicts those curves which potentially should be included in the fusion.[8] The fulcrum bend test seems to be better for thoracic curves relative to lumbar curves, however, we have stopped doing it to keep the imaging efficient and reproducible for our radiology technicians. The indications for an MRI seem to vary from region to region and may be related to the environment and the cost of the scan. We continue to think based on the risk of identifying an abnormality of the neural axis and therefore our indications are asked on the history, the physical exam and the radiographic picture which include: *history*: If the patient complains of dysesthesias in the upper or lower extremities, or uncharacteristic back pain (pain that wakes them from sleep, constant

pain not relieved with NSAIDS); *physical examination*: asymmetric abdominal reflexes, foot deformities (cavovarus foot); *radiographs*: left thoracic curve, lack of thoracic hypokyphosis when a thoracic curve is present[9] or hyperkyphosis measured on the lateral radiograph.[10] In addition to the traditional measurements on the AP and lateral radiograph, it is important to measure the pelvic parameters especially pelvic incidence as this is important when dialing in the sagittal plane correction for each patient. Studies in the adult spine literature suggest that when a pelvic incidence-lumbar lordosis mismatch exists, the incidence of degenerative changes is greater.[11]

4. How do you classify these deformities and how do you use this classification to begin your surgical planning?

SW: With respect to classifications, I use them as a framework for discussion with residents and fellows, but do not rely in any of them in particular to make actual decisions. I have developed my own way of arriving at surgical decision making based on the above-mentioned films, in conjunction with careful examination of the patient noting their rib prominence or paraspinous muscle prominence and their respective flexibility on clinical assessment. As the Lenke classification[8] is the most commonly used, I start with it in our case planning exercises with the residents. I do think it is a good framework for starting discussions but as the readers will know there have been many modifications and add-ons to the original classification scheme which are important also in considering instrumentation levels. The "structurality" of a curve dependent on side bending films, as mentioned above, is heavily dependent on patient effort and the format used to acquire the film. Hence, currently, I place greater stock in the supine film and then looking at the flexibility of each individual curve and how it affects the pedicle rotation to help me decide if I include the secondary curve in the construct.

LA: The Lenke classification remains the preeminent classification system both in our practice and worldwide. I think some of the work on 3D modeling and classification is exciting but not quite to where I am using it in everyday practice.[12]

SS: In regards to the current case, this deformity would be classified as a Lenke 3CN, which implies both the thoracic and lumbar curves need to be included in the fusion. There is no significant kyphosis of the proximal thoracic curve, so I don't feel there is a need to include the entire curve as it is non-structural.

DS: AIS curves that are indicated for surgical treatment should be assessed using the Lenke classification which provides the best framework to identify those curves which require surgical treatment. The classification is easy to use and reliable, however, there is some variability in determining whether the proximal thoracic (PT) curve is structural as the criteria of bending to less than 25 degrees is applied to these very stiff curves.[13] Ultimately, the radiographic classification of each patient needs to be reconciled with the physical examination of the patient to ensure that the appropriate curves are included in the fusion. The clinical appearance should be assessed for overall coronal balance with the understanding that right curves result in a trunk shift to the right, while left curves result in coronal trunk shift to the left. This is important in general and may be critically important when deciding whether a selective fusion is appropriate in the setting of a radiographic double curve. In this example, if the patient has a clinical examination indicating a right trunk shift with radiographs demonstrating a large right thoracic and left lumbar curve, the clinical examination indicates the right curve is dominant over the lumbar curve and helps feeling confident that a selective thoracic fusion is indicated and will lead to an excellent result. Similarly, in a primary lumbar curve, if there is significant waistline asymmetry with a trunk shift to the left then a selective lumbar fusion is appropriate. In general, it is important to look for opportunities to preserve motion segments since the long-term health of

the spine is dependent in general, on two aspects: balance and motion.

5. How do you do your surgical planning for this type of surgery?

SW: In surgical planning for an AIS case, I start by looking at the sagittal plane to determine whether the patient has hypokyphosis and what I ideally would like to achieve in sagittal plane correction or restoration. On both the standing PA and supine AP, I identify a perpendicular to the sacrum to identify the center sacral line to determine the touched, substantially touched, neutral and end vertebra. I next draw a line connecting the superior aspects of the acromion to get an idea of shoulder tilt and also the angle of the T1 superior endplate and superior aspect of the first ribs. I do the same measurements on the supine film. My goals of surgery are to level the shoulders, correct as much of the rotational deformity as possible, and balance the spine both in the coronal and sagittal plane. Distally, my goal is to spare as many lumbar segments as possible in achieving correction and balance. In our index patient, the upper curve goes from 26 to 22 which fits within the Lenke classification as nonstructural. The clinical exam shows the right shoulder as slightly elevated which is also noted on the standing AP radiograph by the interacromial line and the line of the first ribs. I have concerns that on the left side bending film the curve there is still pedicle rotation which must be considered to achieve the goal of level shoulders. In this scenario, I am always concerned that ending the construct at T4 may push-up the left shoulder proximally beyond the ability of the fractional curve to compensate and level the shoulders. While this patient has an excellent radiograph result stopping at T4, the left shoulder is now slightly elevated. Hence, if I have any similar concerns, I carry the proximal extent of the instrumentation fusion to T2. Regardless of my reasoning in this case, each surgeon must develop a method of instrumentation that makes the patient's shoulders level at the end of the procedure. Any shoulder imbalance generally leads to lower patient and parental satisfaction. In my practice, I have tended to use a hook construct at the top two levels relying on ligamentotaxis to achieve shoulder correction so in this particular case I would use a supralaminar hook at T2 on the left side, an upgoing pedicle hook at T3 on the left side, and an upgoing pedicle hook at T2 on the right side. After I had achieved my correction distally, my final maneuvers would involve distraction across the pedicle hook at T3 (T2 hook loosened) then distraction at T2 on the right side and finally compression T2-3 on the left. This method is a carryover from the days when hooks were used, and I continue to find it a very reliable method to ensure shoulder balancing with all pedicle screw constructs. I also have not seen problems with proximal junctional kyphosis using hooks at these levels as opposed to screws. In general, my upper instrumented vertebrae in curves like our index patient is either T2 or T4 depending on the above side bender film caveats.

The lowest instrumented vertebrae are a much more difficult decision for me even after more than 40 years of doing deformity surgery. If I have a structural lumbar curve that on the standing film is more than 45 degrees, even if it has significant flexibility, I tend to include the curve in the fusion area particularly if the patient is skeletally immature. In the index patient, there is significant rotation of the lumbar curve even on the side bending films despite it correcting just under 50%. In this scenario L4 is *substantially touched* with the center sacral line passing just medial to the pedicle on the right side. In idiopathic patients (children), I never extend fusion below L4 and in this case try to stop but L3 if possible. I make my final decision in this case in the operating room with the patient anesthetized and prone doing a *push prone* image. If I feel I can completely derotate L3 and horizontalize it to the sacrum I will stop the construct L3. As I have chosen to fuse the lumbar curve in this scenario and my decision is whether to stop at L3 or L4, I feel somewhat comfortable knowing that if coronal and sagittal balance are restored, long term results will be acceptable. With that said, intuitively one would like to fuse as few segments as possible, so I

would like to stop at L3 if on the above-mentioned push prone intraoperative films support that decision.

The question of implant density related to outcome is somewhat controversial. As the cost of implants has moved AIS surgery to the number one surgical cost item in children 10-18 years of age, this question will become much more important in the evolving healthcare delivery paradigms. The recent "MIMO study" has addressed this question in Lenke 1 curves with no differences in high- and low-density constructs. There are many studies in the literature including older studies using all hook constructs which show excellent curve correction in both the coronal and sagittal plane and good clinical outcomes. Pedicle screw constructs can significantly improve the patient's rotational deformity and better restore balance. In the lumbar spine, I tend to use uni-planar pedicle screws at each level on both sides so that I can control rotation. I also try to use screws at every level on the concavity of the thoracic curve but certainly in the periapical area I also like to have two implants proximally for better fixation. I do all my screws freehand so that if a pedicle is too small for a screw, I prefer not to go along the lateral boarder of the pedicle and into the body (out in technique), but instead I prefer just to skip the level. I am always prepared to use a hook if necessary, to achieve my ultimate goals. On the convexity, I try to ensure that I have periapical screws to help derotate the thoracic apex and then as mentioned above two fixation points proximally. If the thoracic curve is very flexible you can use uni-planar screws throughout the construct on the concavity in the thoracic area. Most often I would use poly-axial screws but when I do my corrective maneuvers I use either uniplanar convex apical screws or use multiple screwdrivers in the screw heads of poly-axial screws at the periapical convexity to derotate the spine as I also use the reduction screws to further derotate and pull the spine to the concave rod in the thoracic spine to derotate and restore kyphosis. I tend to use 5.5mm rods and titanium and cobalt chrome implants. I think it is important for each surgeon to understand the mechanical properties of the system that they use, which includes the modulus elasticity of the rods as many companies have multiple rod stiffness in the same diameter. It is also important to be aware of the patient's bone quality and always be on the lookout for screw pullout or plowing, both of which could have serious consequences. I make liberal use of in-situ bending to ensure good correction and carefully monitor the bone screw interface at each level.

LA: "Start with the lateral" has been a mantra at our institution, this way you make sure you don't forget to consider it (no one ever forgets to look at the AP). For me this has three components:

1. Check for spondylolysis/spondylolisthesis, which can be seen in 10-15% of AIS patients. It is embarrassing as a spine surgeon if you miss that and it later comes to light.

2. Look at the sagittal profile and determine if that makes any of the minor curves structural (this is one of the points of the Lenke classification that people sometimes forget to pay attention to; for example if the T2 to T5 kyphosis is more than 20 degrees then the proximal thoracic curve is structural and you will get burned if you don't include it).

3. I draw the posterior sacral vertical line to determine the stable sagittal vertebra line and know I shouldn't have a LIV above that if possible.

Then I switch over to the PA and bending views. From these we can determine that both the main thoracic (major) and lumbar curves are structural (this should also coincide with our clinical exam), but the upper thoracic is not (bends out to less than 25). From that I conclude that I would include both main thoracic and lumbar curves. Since the upper thoracic curve is not structural, then I usually go by T4 for high right shoulder (which this is by clinical description though it is subtle on radiographs), T3 for level shoulders, T2 if the left is high. For the LIV, typically you would use the vertebrae just touched by the center sacral line, but this is one area where we frequently "break the rules" and especially with L3 vs L4 have some significant potential benefit

from doing that. Some indicators that you can probably do that here are that the disc between L3 and L4 opens in both directions and that the L3 to L5 segment lines up nicely on the left bending film. My current typical constructs is basically screws at every level on the left (my side), it seems easiest for me and my team to just get in a rhythm and stay with that. On the right (resident side), I template for two anchors at the bottom, two at the top and two to three at the apex of each curve so that I can use triangulated/linked vertebral column manipulators to derotate at those levels. For AIS, I generally use all screws unless there is a particularly uncooperative pedicle. For typical AIS curves such as this one I prefer 6.0 CoCr, its strong but easier to work with than stainless steel. However, intraoperatively if the curve is stiff or the fixation points are not as strong as anticipated, then I will switch to 5.5 or even titanium (I also often switch if there are signal issues).

SS: I start with a detailed exam of the radiograph, with special attention to the lateral and 3D views reproduced using the EOS system. The areas I concentrate on are the rib hump offset, need for thoracic kyphosis correction, and preservation of lumbar lordosis based on radiographic pelvic incidence. Once that is one, make sure your understanding of the radiographic deformity matches that of the patient's clinical appearance (often photos of the patient from clinic are helpful if planning at other times). I then determine the UIV based on the shoulder appearance: T2 if left shoulder is elevated, T3 if shoulders are level or if a large main thoracic correction is planned, and T4 if right shoulder is up. I try to have the LIV be the last touched by center sacral vertical line (LTCSVL), but almost never to L4. In general, I will include all structural curves in the fusion, unless the patient is an elite athlete and you can push indications for a selective thoracic fusion to leave the lumbar spine flexible. I tend to target an overall implant density high (1.8 or more), placing uniplanar pedicle screws at almost every level (but feel it is ok to drop 2 screws on convex side most of the time). As for my rod, I use a 5.5mm CoCr or ultra high stainless steel rod.

DS: The initial steps to surgical planning are to first determine which curves require inclusion in the arthrodesis and then to decide which specific vertebral levels to instrument and fuse. The physical examination is the most important aspect to determining which curves require surgical treatment and includes an assessment of shoulder elevation, coronal balance, rotational deformity of the potential curves, and waistline asymmetry. The radiographs should then be assessed and a comparison of these images to the physical appearance of the patient is then made. In general, the physical examination of the patient supersedes the radiographs if there are any discrepancies noted. For example, if the left shoulder is elevated despite the radiographs not demonstrating a structural PT curve (because the curve bends to less than 25 degrees), it is important to include the PT curve to ensure that shoulder balance will be achieved following surgery. For the case presented, the patient has a slight trunk shift to the right suggesting that the right thoracic curve is "dominant" over the left lumbar curve and the right shoulder is higher than the left so that the left proximal curve is not structural. The lateral radiograph demonstrates significant thoracic hypokyphosis as the apical rib heads are in a straight line and even slightly lordotic indicating an idiopathic type curve. There does not appear to be any junctional kyphosis between the proximal thoracic and main thoracic curves or between the MT and TL/L curves which in and of itself suggests that the PT and TL/L curves are not structural. However, the curve magnitudes of the MT and TL/L curves are similar, they have significant and similarly large apical vertebral translations (AVT) and apical vertebral rotations (AVR) and the bend films demonstrate both curves bending short of 25 degrees. Using the Lenke AIS surgical classification, the MT curve is the largest and automatically requires fusion, the lumbar curve is large, has significant AVT and AVR, and does not bend to less than 25 degrees while the PT is not large, bends to less than 25 degrees and the right shoulder is elevated and so the classification is 3C curve. The most conventional treatment for 3C curves is to fuse both the MT and TL/L curve, however, the option of a

selective thoracic fusion (STF) can be considered with these relatively modest curves, supine best bend radiographs of the lumbar curve near 25 degrees, a more skeletally mature patient (limiting progression of the uninstrumented lumbar spine) and a patient who can accept less deformity correction. The risk is decompensation to the left as the lower half of the lumbar spine continues to demonstrate tilt to the left creating this trunk shift. However, once fusion is performed progression of the lumbar curve is relatively unusual in long-term followup.[14,15] With posterior fusions for 3C curves the upper instrumented vertebra (UIV) is generally the UEV which is often T4 or T5 and it is best to see that planned UIV be in the midline. If there are any concerns with the left shoulder being elevated, the more proximal UIV can be selected and to fully control it, one can go to T3. In this particular patient the UIV selection would be T4 as was performed. The LIV selection is often where the controversy lies. For this case, both curves would be fused and the starting point to determine the LIV for all lumbar curves is the lower end vertebra which in this case is L3. The controversy here is that the L3-4 disc is parallel indicating that L4 is tilted into the curve and is not tilted into the fractional lumbosacral curve and may not become horizontal following fusion to L3. The resulting tilt of L4 risks potential disc wedging at L3-4, whose ultimate future is uncertain and may risk trunk shift to the left. However, several factors indicate that an LIV at L3 provides excellent correction without the above problems: this is a relatively modest lumbar curve, the left bend film demonstrates a flexible L3-4 disc, as it opens to the right, and the right bend film demonstrates that the L4 vertebra becomes nearly horizontal relative to the pelvis.

Implant density should be "dosed" based on the diagnosis, stiffness of the curve, deformity correction desired, the correction mechanics employed and the experience of the surgeon. The MIMO (minimal implants maximum outcome) study analyzing single thoracic curves between 45 and 65 degrees could not demonstrate a difference in the primary outcome comparing high and low-density screw patterns. In addition, it is important to realize that every screw should be used to its full potential, strategically placed to specific vertebra, to achieve maximum correction and a justification for each screw should be outlined. In general, four screws are necessary at the end of the construct, the apex requires higher screw density especially on the concave side and the lumbar spine requires significant rigidity to provide return to physical activities during the process of fusion and a higher screw density. I prefer stiffer cobalt-chrome rods for the "correcting rod" to achieve three-dimensional correction with excessive kyphosis contoured for the thoracic curve and an undercountoured right less stiff (small diameter Co-Cr rod or titanium rod). When instrumenting both curves in this case, it is critical to get the lumbar curve corrected nearly completely in all planes.

6. How do you determine the need for osteotomies and how do you determine where to place these if needed?

SW: When osteotomies are needed, I use the typical Ponte osteotomies as described in the literature. Even if I do not do osteotomies, I do complete inferior facet joint excision, remove the spinous processes to the level of my inferior facet excision, and thin the ligamentum flavum significantly at each level to allow maximal mobility. If I need or decide to do a Ponte osteotomy, then I merely excise the already thinned ligamentum flavum and the superior facet joint in each side all of which I do with a Kerrison rongeur. I find that in most idiopathic patients Ponte osteotomies are not necessary as with the above facet, spinous process and ligamentum flavum thinning technique excellent mobility can be achieved and good corrections obtained both in the sagittal and coronal plane. This may require significant and controlled in-situ rod bending. If, however, the curve is extremely rigid or very large (greater than 75 degrees) then I consider using osteotomies after I have my screw holes tapped and packed with Gelfoam to minimize bleeding. After I have done the Ponte osteotomy, I put my screws into the tapped hole and

leave some Gelfoam across the open osteotomy site. If I do Ponte's they are always across the apical area of the curve. When I do my final correction, I remove the Gelfoam to avoid any spinal cord compression. This usually is not a problem in scoliosis correction but certainly can be a problem using Ponte osteotomies in kyphosis correction. If there is any gap with the osteotomy, I place a small pad of Gelfoam across it there to prevent bone chips from entering the spinal canal. If I am planning to do Ponte osteotomies in advance, then I will prepare the pedicle screw sites above and below each osteotomy but not place the screws until I have done the osteotomy to prevent the hardware from interfering with my ability to do a wide osteotomy from pedicle to pedicle ensuring that the neural foramen is completely open. Ponte osteotomies add to the potential blood loss and hematoma formation and to the increased risk of neurologic deficit so hence I do them when necessary but not routinely.

LA: For me the debate of whether or not to do Ponte osteotomies is a "when and how" not "if" question. I think they are very beneficial for improving your derotation so if clinically the rib prominence is severe then I will be anticipating doing them. Additionally, if the curve is still large on the bending films then I am anticipating doing some, but the extent to which I do is largely determined intraoperatively following the facetectomies. I use the powered Kerrison (or sometimes just ultrasonic bone scalpel) for these and with that it is pretty quick to add them. It's really unfortunate to do your correction and then realize you needed more, so I err on the side of more not less.

SS: Always as the principle is to mobilize the spine. I typically do these osteotomies before inserting my screws in about four to five levels at the thoracic apex.[16]

DS: The use of posterior column (Ponte) osteotomies in AIS is somewhat controversial and in general, I employ the same strategy as screws in that they are only necessary to properly dose the amount of correction needed for the deformity. It should be remembered that Ponte first described these for primarily sagittal plane deformity (hyperkyphosis and Scheuermann's kyphosis) and it is clear they are necessary and effective in these patients. However, biomechanical studies,[17] and clinical studies have demonstrated no or very little deformity improvement when Ponte osteotomies are utilized in the setting of AIS.[18,19] For those studies which have demonstrated improvement in curve correction with Ponte osteotomy, the percent improvement compared to no osteotomies appears to average about 6% which is only 3.7 degrees for the 62 degree curve presented here.[20] We recently compared a matched group of larger AIS curves averaging 70 degrees demonstrating improvement of 7% of coronal plane correction, with no differences in improvement in sagittal plane correction or clinical rotational deformity correction or SRS-22 scores.[21] What we did find was a significant increase in the incidence of intraoperative neuromonitoring changes, increased blood loss and operative time, findings seen with other studies as well. There is no doubt there is value in performing these osteotomies in large curves with significant deformity or in scenarios in which full correction is desired such as a large lumbar curve in which these osteotomies may have greater value as the restriction of the thoracic cage does not limit the flexibility provided by the osteotomy. When performing these osteotomies, it is important to ensure safety to the spinal cord and to limit the blood loss seen when the canal is exposed with epidural bleeding. The order in which the implants are placed, and the performance of the osteotomies assist in limiting these complications. I typically prepare the screw tracks, including tapping the track on both sides of the intended osteotomy, followed by performing the osteotomy, and using some thrombotic agent followed by a cottonoid pattie to prevent bleeding and to protect the cord. The screws can then be safely placed, followed by repeating the same steps until all of the Ponte osteotomies are performed.

7. How do you optimize patient positioning in the OR to help with correction?

SW: I always position patients prone on the OSI table replicating the standing position. I have the hips fully extended, knees extended on pillows with the feet free to allow for observation of monitoring changes and during the wake-up test should this be necessary. I use a standard four-poster OSI frame padding of the iliac crests and lateral to the breast with the breast tucked medially in female patients. The arms are abducted about 20 degrees elbows flexed to 90 with padding under the forearm, keeping the ulnar nerve free. The key for me is placing the patient in the standing position, which helps me ensure that I have good coronal and sagittal balance and that my films are taken in the appropriate position. I tend not to use traction during surgery or place temporary distraction rods unless the curve is very severe, and I am going need to rely on tissue relaxation. For the standard AIS patients such as our index patient, these types of techniques are in my opinion rarely necessary.

LA: We use a Jackson table which has a pretty large chest roll that helps with creating some thoracic kyphosis. Additionally, you want to make sure your shoulders and hip positioning is symmetrical.

SS: We use cranial tongs for bigger curves and traction when necessary. I will adjust the chest pad to aid with thoracic kyphosis restoration, sometimes even adjusting intraoperatively before rods go in.

DS: The patient's positioning is the first part of the procedure and allows one to begin to gain correction but should also ensure safety (no pressure on the eyes to avoid the rare occurrence of blindness, and proper arm positioning to avoid brachial plexus stretch). The arms should be positioned at 90 degrees to the body on an adjacent arm board with egg crate padding underneath to protect the ulnar nerve. The arms should be fully supported to limit excess traction to the arm and there should be two fingerbreadths between the top of the chest pad and the axilla to avoid excess pressure. The abdomen should be free to avoid inferior vena cava congestion and venous pooling and so the hip pads should be at the level of the anterior superior iliac spine and I most often place them more distal especially for those patients in which we are instrumenting into the lumbar spine. In this way the hips can be extended to improve lumbar lordosis when more is desired. The distal position of the lumbar pads risks compression of the femoral nerve which is rare and also can result in compression of the lateral femoral cutaneous nerve which is relatively common. For very large curves (>85°) and especially those who have been in preoperative traction, the patient is put in traction utilizing Mayfield tongs proximally and distal pelvic traction. The distal pelvic traction is applied by first placing Benzoin along the lateral flank ending proximal to the iliac crest to ensure there is adequate surface area for the skin tapes to be adherent to. The skin tapes are then placed beginning proximal to the iliac crests and continued distally. The weight is applied centrally in the typical AIS patient but can be applied asymmetrically if there is significant obliquity (most often seen in the neuromuscular patient). The weights should be applied sequentially with evaluation of intraoperative neuromonitoring (IONM) with each increase. Usually weights of 20-30 pounds are used on the head with 30-40 pounds on the pelvis. The weights should be significantly decreased following rod insertion as the traction then is only being applied proximal to the construct and IONM changes and neurologic deficits can occur.

8. What are your tips and tricks for blood management in the operating room?

SW: Over the years, I have gone away from using any hypotensive anesthesia and currently just keep the patient's normotensive, normothermic, and rely on meticulous surgical dissection techniques and as short as possible surgical times to prevent blood loss. We use tranexamic acid (TXA) preoperatively with a 50 mg/kg bolus and then 10 mg/kg continuous infusion until the wound is closed and dressings were applied.[22] Generally,

the exposure can be done without any excessive blood loss. Most of bleeding comes with pedicle bleeding with screw hole preparation (gearshift and tapping). I will put a pad of thrombin-soaked Gelfoam into the pedicle just before I insert the screw to keep pedicle oozing to a minimum. I pack with sponges all areas that I am not working on. I usually instrument from distal to proximal keeping the area that I am not working on packed with sponges. I sometimes use additional fibrillar or Gelfoam as needed. We rarely ever transfuse patients in the operating room. I have *not* used the cell saver in over 25 years as we never loose enough blood in the operating room in idiopathic patients to warrant its use.

LA: We use TXA, which I think is pretty standard now. Anesthesia has a protocol for controlled hypotension during exposure and instrumentation, and then raising the blood pressure to 75 mm Hg when we are getting ready for correction. Also, the ultrasonic bone scalpel for facetectomies seems to decrease the blood loss.[23]

SS: We use TXA (30mg/kg bolus and a 10mg/kg infusion) during the case. The electrocautery is set on 55-60 during bone dissection and the mean arterial pressure is targeted at 60 mmHg for exposure. We use the ultrasonic bone scalpel for facetectomy and Pontes to limit blood loss during these procedures. Cell saver is used for all cases except anterior and selective thoracic fusions.

DS: Blood loss during AIS surgery can vary significantly based on some non-modifiable parameters that may be patient specific with increased blood loss for larger patients, those with larger curves, and when fusion levels are greater. Other factors are surgeon-specific and are in part, dependent on the expertise of the entire surgical team as they work together to accomplish a safe and effective surgery.[24,25] Coordination with the anesthesiologist should occur to ensure that the mean arterial pressure (MAP) is relatively low (60 mm Hg) during dissection and screw placement which helps keep blood loss low. The MAP should then be increased (>70-80 depending on the deformity) from the time the correction maneuvers begins until the completion of the surgery to ensure excellent perfusion to the cord during these stressful times. Efficiency in the operating room which shortens surgery appropriately, and careful surgical technique are critical to limiting blood loss. Some specific techniques which seem to be helpful include setting the elctrocautery to 60 for both the coagulation and cutting modes but ensuring that this instrument is used with relatively swift movements to avoid burning the tissues. The Cobb elevator should be always placed subperiosteally and during stripping should never travel past the distal edge of the spinous process of the segment being stripped since this is the location of venous bleeders. The ultrasonic bone scapel is not something that I use but may have benefit when multiple osteotomies are performed. Similarly, the Aquamanys is something I use only for patients with neurofibromatosis in the setting of large neurofibromas which are in the soft tissue areas we will encounter in surgery and is very effective. These two tools are seemingly used routinely for some and their benefit must be balanced against their cost and time to set them up.[26] Power instruments allow for placement of screws in a very efficient manner which allows for smooth and easy transitions during the typical sequence of screw placement.

9. What is your standard deformity reduction technique for this type of deformity?

SW: After the exposure in a patient such as our index patient, I would be placing the left-sided rod first. I measure using the cautery cord for length and then I cut and contour the rod as I would like to see it in the sagittal plane, restoring kyphosis in the thoracic spine. I would be capturing the rod at every level that is instrumented. I would first derotate the lumbar spine with the uniplanar screws which I use in this region; I would provisionally tighten these screws, as I will return to these later. I would then work on the thoracic spine from the neutral vertebrae at T10 and T11 working proximally leaving my hooks loose at T2 and T3 so as not to affect their purchase. I would put multiple

screwdrivers in the apical vertebrae screwheads (as these are polyaxial screws you cannot rotate through the tulip- or I would use some peri apical uniplanar screws) I would derotate the spine and use the reduction screws on the concave side to help derotate the spine and pull the spine to the rod to create additional kyphosis in the thoracic spine. Assuming I achieve satisfactory correction, I would then start working to the right-sided rod. If I felt I had residual coronal deformity, then I would use the side to side benders with the screws very loosely tightened so as not to disrupt the bone screw interface, to get additional correction allowing for relaxation over time. Once I am satisfied with my correction in the coronal plane and somewhat in the sagittal plane with the left-sided rod, I would measure, cut and contour my right sided rod. In this right sided rod, I tend to contour the thoracic spine with minimal kyphosis as I tend to use this rod to "push down" and derotate the ribs on the curve convexity. Similarly, I bend the lumbar segment a bit less with lordosis to help derotate the lumbar spine further. I then use my bilateral lumbar uniplanar screws in addition to an occasionally applied external force via a mallet over the apex of the lumbar curve to completely derotate the lumbar coronal deformity and horizontalize the lowest instrumented segment to the pelvis. I then do my final tightening of the rod in the thoracic spine on the concave side further pulling the vertebrae to the rod and correcting rotation with some additional restoration of the thoracic kyphosis. Once the main thoracic and lumbar curves are stabilized, I do my shoulder leveling by distraction across T3 on the left with a T2 hook loosened to allow me to push up on the left shoulder, then I distract at T2 on the right relying on ligamentotaxis to balance the shoulder on that side. Finally, I compress the T2-3 "claw" on the left to secure these hooks. I check balance with the fluoroscopy looking for horizontalization of all the cervical vertebrae and the upper thoracic vertebrae and then I check with fluoroscopy distally looking for horizontalization of the distal portion of the spine. If I have any concerns about balance, I can use a "T square" across the iliac crests with the perpendicular at the sacrum and check for balance on a full-length 72-inch film in the operating room, this is rarely necessary in AIS patients such as our index patient. With hooks is also important to use a cross-link so in this case I would have a cross-link applied distal to T2 to give increased rotational stability by approximately 25%. Cross-links are not used distally in the screw construct area.

LA: For the double major curves, I have changed my approach a lot in the last year or so. I now do an aggressive differential rod bend and anchor the rods proximally first, lock the rod orientation in up top and then use serial reducers to seat it distally but leaving the rest of the set screws loose. Ninety percent of the correction occurs with that. Then I follow with triangulating the vertebral column rotators at the apex of the thoracic and lumbar curves, derotating the vertebrae and fastening that in place by tightening the set screws. I follow that by fine-tuning with compression and distraction to balance the UIV and LIV. I like this better than what I did before because it seems to "lock" the lumbar derotation in place.

SS: I think rod contour is very important. I see a lot of rods underbent to restore thoracic kyphosis, and the ends of rods are too long or too lordotic (remember the majority of LL comes at L4 and below, even in high PI cases). Remember to bend enough proximal thoracic kyphosis to avoid radiographic PJK. When contouring the rods, avoid notching the rod, bending and rebending, and always have smooth contours, no abrupt bends. I first put in my left rod, no rod derotation at this time, just translational correction by bringing spine to the rod. I use differential rod bending with a hyperkyphotic bend for concavity of thoracic curve, more lordosis on convexity of lumbar curve. The right sided rod is similar contoured in the proximal thoracic region, but much flatter for both the thoracic convexity and lumbar concavity. This accomplishes much of the axial plane correction. Both curves are corrected simultaneously, or whichever will come over first. Only one set screw is tightened to keep rod properly oriented in the sagittal plane while the other rod is implanted. Then, set screws

are tightened segmentally as axial plane is corrected via segmental direct vertebral rotation. I address the axial rotation, I always uniplanar screws and segmental dertotation while final tightening. I typically will retighten the set screws 5-10 minutes later, to avoid slip. It is difficult to get the shoulders perfectly level, so I set modest expectations in preop counseling. Intraoperativly, look to get T1 level, as I find that is about the only thing we have modest control over. Leveling the LIV is usually desirable, and I would try hard to get it right for this case. I would use compression/distraction while simultaneously derotating the LIV to neutral if it is not spontaneously so. Look at LIV+1 – does it look perfect? If not, it won't look any better when she stands up, so get it right in the OR!

DS: I prefer to start this process by placing derotators on the convex side of the lumbar spine to correct and derotate the lumbar curve followed by a temporary right-sided lumbar rod. Now the lumbar curve is partially corrected, and the left rod can be placed engaging the rod partially in the left lumbar spine while engaging only the top screw(s) of the thoracic curve leaving the overcontoured rod posterior to the apex of the thoracic spine. The temporary right lumbar rod is removed and correction of the spine using the left rod begins with the apex of the thoracic curve pulled to the rod with reducers and the lumbar curve corrected as partial rod rotation to complete the axial plane correction. Compression is used to complete coronal and sagittal plane correction and to horizontalize L3. Further apical derotation maneuvers can be performed for both the thoracic and lumbar curves. The right rod is under-countoured for both the thoracic and lumbar curves to push down on the thoracic apex and to pull up (posterior) on the lumbar apex. Slight distraction may be necessary to fully horizontalize L3 and does not jeopardize lumbar lordosis as this was set in place with the left rod. In-situ bending of the rods in the coronal plane provides opportunities to improve correction and generally are performed at the apex and prior to compression-distraction maneuvers. The variety of reduction and correction mechanics allows one to perform these multiple times over several rounds of correction to achieve the desired correction.

10. How do you judge your correction in the operating room?

SW: I judge my correction through intraoperative fluoroscopy as mentioned above or on occasion a 72-inch films taken in the operating room but again, I find this rarely necessary. I make my decisions about whether I need to do more or less well before this point in the surgery. I make continual assessments along the way, never at the end. I may take a quick fluoroscopic view if I have any concerns. I also visibly look at the patient's chest deformity as I have this area completely draped out from posterior axillary line to posterior axillary line.

LA: We have a T-square that I center first on the hips to make sure the upper portion is traveling through the center of T2 so I know coronal balance has been achieved.[27] Then I flip it around and center it on the coracoid processes to judge the shoulder balance. I aim for a level LIV, and for the UIV, I find you often have to leave that tilted down to the left a little to have T1 and the shoulders balanced.

SS: I use fluoroscopy to look at the overall appearance of construct, specifically are screws pointed medially to judge my axial plane correction. Then I use an intraoperative O-arm spin after screws are in to avoid malpositioned screws.

DS: Every spine deformity surgery at our institution has a 3-foot film obtained from an overhead-mounted X-ray machine in the OR. The checklist for the assessment of this image is: screw position, correct fusion levels, correction and we always ensure both lungs are inflated by ensure there are lung markings out to the periphery. The correction parameters identified on the coronal view include assessing how close we achieved the desired correction of the coronal deformity, assessment of the rotational correction, assessing shoulder balance, being sure T1 tilt is minimized. For this particular case where

the fusion was extended into the lumbar spine, the LIV should be horizontal. If this is not seen on the images, then further compression on the left side and distraction on the right can be performed. What is unknown is what will happen below the LIV and specifically will the L4 vertebral tilt improve significantly enough to maintain coronal balance and provide good long-term health of the spine. There are no known predictors for how much disc wedging is acceptable, but it is fair to suggest that less than 10 degrees of disc wedge will result in long-term good outcomes especially when compared to the alternative of fusion to L4. We have unpublished data to suggest that the intraoperative disc wedging changes by less than 5 degrees between the supine intraoperative film and the 2-year radiograph as long as the patient is not skeletally immature indicated by open triradiate cartilage. An intraoperative lateral radiograph can also be obtained to assess the overall sagittal profile, thoracic kyphosis, and lumbar lordosis. These parameters are less necessarily checked for a selective thoracic fusion since restoration of thoracic kyphosis is achieved under direct visualization and modifying this parameter following the completion of correction is difficult. The lateral to check screw lengths is not usually necessary depending on the method of placing screws using fluoroscopy or navigation.

11. What is your immediate postoperative patient protocol?

SW: Most patients are mobilized to the sitting position the night of surgery. Postop day #1: they are out of bed; catheter removed; transition from intravenous to oral medication with some nurse directed boluses on the first postoperative day to supplement oral pain medication; begin oral intake advancing to clears on day one with the return of bowel sounds then as tolerated to soft diet and full diet usually on the following day. The Hemovac which is placed in the subcutaneous space (not deep) is removed at 36 hours postop. Most patients are discharged on the third or fourth postoperative day. Our postoperative dressing consists of mesh skin glue dressing (Dermabond Prineo) covered by waterproof Mepilex AG postop dressing. This is removed by the family at 2 weeks postop.

LW: All patients are followed by our pain team postoperatively and their management follows a protocol. The key components of this in addition to the intraopaerative intrathecal morphine are one. Stopping the PCA on day one and transitioning to oxycodone and valium two. They also get Toradol and Neurontin to help minimize narcotic use. For mobilization, they sit at the side of the bed with nursing on POD O and then mobilize the following day with PT a few times a day with nursing and family following PT.

SS: We were among the first to use gabapentin and Toradol to decrease morphine equivalents, so lots of experience with rapid recovery pathway.[28] Now, on top of that, we use a clonidine patch, get on oral pain medicine on POD 1 with oxycodone, Tylenol. and valium. The patient sits up in bed in PACU and typically is admitted to the floor the first night, with something to drink. To advance mobility we expect the patient to be out of bed to the chair twice on POD 1 and walk in hall on POD 2, with stairs should be cleared by the end of POD 2 or 3. With this protocol we have been able to achieve an average length of stay of 2.7 days.

DS: Our patients have an epidural catheter placed at the time of surgery with administration of rupivicaine, together with continuous intravenous dexmedetomidine (Precedex®) without narcotics except for Dilaudid prn. The epidural provides excellent pain relief allowing for a restful night, so they are ready for mobilizing the next morning. The patient is given oral meds and if tolerated the epidural is removed at 11 am, together with the arterial line and foley catheter. The patient is in a chair for 1 hour, back to bed and then up walking laps 2 hours later. Walking is done 3 times per day and in patients with a thoracic fusion only the patient is usually discharged the second postoperative day. If the fusion extends into the lumbar spine, the patient is usually discharged on POD 2 or 3.

12. What is your longer-term postoperative and follow up protocol?

SW: Patients are seen at 6 weeks postoperative by our ARNP and encouraged to increase their activity level, particularly aerobic activity. The next visit is at 3 to 4 months postop and if doing well, then we begin aerobic exercise including jogging, walking on a treadmill, light hand weights, TheraBand exercises, and chair pushups. Some of our more athletic children we let them begin with a kick board and then "easy swimming" (crawl). We release them to full unrestricted activities at 6 months postop. All patients have no permanent restrictions but for the male patients I generally do not recommend tackle football or competitive wrestling (no data to support these restrictions just my intuitive feeling of too much risk). I see the patient is at 1 year postop, 2 years postop, and 5 years postop and then PRN.

LA: I obtain an upright PA and lateral at the time of discharge to confirm that everything looks appropriate prior to when they go home. I don't repeat those until the one-year mark unless there is a clinical concern.[29] My typical follow up is:

Two weeks: A visit to make sure the incision is healing and that they are off pain medication or close to that;

Six weeks: Confirm they are back at school and doing OK (most return around 3 weeks though this varies). I release them to light activity/reconditioning at that time;

Three months: Release to full sports participation;

Six months: Confirm that they are back to everything from before surgery and don't have any additional concerns;

One year: Repeat radiographs, which I continue to repeat on an annual basis until 3 years, and then every 2 years following that.

My patients have my cell phone, my PA's phone, as well as the office nursing line so it is pretty rare that there are major surprises that come up at the follow up visits.

We don't give any long-term restrictions but do explain to patients and parents that there is likely some increased risk of spine injury with participation in contact sports. I tell them I believe this to be small given that I am aware of only a few cases in many 1,000s of patients returning to sports but that it is impossible to quantify. In the absence of level 1 data on this subject, we all have to share that theoretical risk and balance it against the known benefits of sports participation.

SS: I will see the patient back at one month for an erect X-rays in the EOS. I then see them back at 6 months, 1, 2 and 5 years postop and a final visit at 10 years postop (when I can get them in before 21st birthday) In terms of return to activity, I allow light housework immediately, return to school at 3 weeks, light sports (swim, elliptical, bike, treadmill) around 6 weeks, and most sports 3-4 months. I allow contact sports at 6 months.

DS: Following discharge, the patients are allowed normal ADL's and can perform mild-to-moderate activities. They are seen for a return visit at 6 weeks at which point a radiograph is obtained and if the patient is doing well their activities are advanced over the next 6 weeks with two levels of expectations. For thoracic curve fusions, the patient is advanced to full activities without restrictions and is seen back at 1 year from surgery unless there are concerns by the family. If the fusion included a lumbar curve or went distal to L2 for single thoracic curves the patient is advanced from the 6 week to the 12-week time period but is not allowed to participate in contact (soccer, basketball, lacrosse) or collision sports (hockey, football) until the 6 month time period at which point a visit is done to assess the patient clinically and radiographically.

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