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Fixation techniques in revision spine surgery☆

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ABSTRACT

The purpose of this chapter is to provide a detailed description of the intra-operative technical steps required for advanced reconstructive procedures used for revising failed or incomplete spine surgery. There is a growing incidence of primary, and with it, revision spine surgery. Fixation often becomes a challenge with increasing population age, comorbidities, and multiple attempts at instrumentation. Herein we detail: screw cementation, quad rod constructs, dural scar resection, PJK prevention, and navigation and robotics. This work provides working descriptions of techniques that may be of use to practitioners of complex spine surgery.

1. Introduction

The number of spine surgeries performed in the United States has demonstrated significant increases on an annual basis.[1–3] Approximately 122,000 lumbar fusions were performed in 2001 alone which represents a 220% increase from 1990. In addition, between 1998 and 2008, the rate of fusions increased by 90% for cervical, 61% for thoracic, and 41% for lumbar fusions.[4] As the rates of surgeries continue to increase, the rates of complications, incomplete success, and failure of these procedures rise as well. This has led to an increasing need for revision spine surgeons, surgeries, and techniques.

Complex problems, some the result of patient lifestyles, others the result of an aging population lead to failures of biology or instrumentation associated with iatrogenic adult deformity, failed back syndrome, or adjacent segment disease. In addition, recurrent or persistent bony stenosis, intractable radiculitis, epidemic axial back pain associated with multiply revised spondylotic spines with paraspinal muscle degeneration create a challenging new revision patient population. In this challenging environment, knowledge of revision techniques constitutes the important armamentarium of spine surgeons endeavoring to advance the front lines in the battle of revision spine surgery.

Index surgery complexity, nicotine use, secondary gain like worker's compensation, and disease processes or medications that affect bone health all have been linked to increased complications and increased need for revision surgery.[5–9] Variability in practice patterns, indications, compliance with evidence-based guidelines, market diversification of spinal instrumentation, and differences in training and technique among surgeons create an unreliable milieu for spine patients wondering about expected outcomes and the scientific basis for revision surgery.

Compounding the riskiness of revision procedures are the comorbidities, complications, hospital length of stay, and overall cost[10,11] associated with revision spine surgery. Optimizing management of these patients requires meticulous (1) pre-operative planning for hemostasis strategies, multi-disciplinary anesthesia rounds for diabetes and COPD management; high-quality CT myelogram and MRI imaging and close working relationships with MSK radiologists. (2) Peri-operative preparations must also be made for equipment

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availability and cost allocation to include neuromonitoring (EMG's, SSEP's, motors), ultra-sound bipolar electrocautory (Aquamantys), red blood cell recycling technologies (Cell Saver) as needed. And most importantly, (3) the actual intra-operative surgical technique for which the head surgeon alone must be ultimately responsible is necessary.

The lead surgeon's judgment determines the course of intra-operative decision making. Beyond leadership skills, the technical skills of the head surgeon are difficult for non-expert ancillary staff to assess, and the surgeon alone must be honest about their level of proficiency with the various skills and techniques to be performed.

We have found certain techniques commonly employed for revision spine surgery and will share some of these in this paper. These include cement augmentation of screws, multi-rod constructs, dural scar resection, posterior tension band reconstruction, various proximal junctional kyphosis prevention techniques, and navigation and robot assisted surgery. Where initial management has failed, finding advanced techniques to safely navigate and operate in a challenging surgical environment is of paramount importance. Revision spine surgery is a frontier that prioritizes surgeon technical proficiency as the pre-requisite to a better outcome.

2. Cemented pedicle screws

Cementation is a process of using polymethylmethacryalte (PMMA) to augment the strength of implantable constructs especially as it applies to osteoporotic bone or bone that has been "swiss-cheesed" by multiple revision instrumentation attempts.[12]

Biomechanical strength: Studies have shown that the addition of PMMA in previously instrumented or osteoporotic vertebrae results in restored or even increased screw pullout strength.[13–15] Amendola et al. found that up to 2-3ml of liquid PMMA has been suggested to maximize screw fixation in one biomechanical study. It was found however that using beyond 3ml of PMMA did not produce increased screw fixation strength or resistance to pullout while resulting in a significant increase in the rate of extravasation.[16]

Fenestrated screws for PMMA application (Fig. 1): The screw tip should be placed as deep into the body of the segment as possible without violating the anterior cortex. This will maximize the distance between the shallowest fenestration and the posterior cortex of the body through which the cement is at risk of extravasating directly into the spinal canal if screw depth is inadequate.

Regarding sequence of cementation[17] some surgeons advocate a caudal to cranial order of progression for cementation (Lumbar to Thoracic to Cervical) because starting with the lower viscosity cement, which is associated with leakage, is safer around the larger (caudal) canal diameters and allows for hardening to occur as the more cranial segments are approached, where canal size and cord presence are much less forgiving. This assumes a single batch of PMMA. This minimizes the risk of neurological injury.

Needle injection versus cannulated screw method: In 2013 Chang et al.[18] compared the two methods. The results showed that while clinical outcomes were satisfactory in both groups with no significant difference, pullout strength of the needle injection group was significantly higher than the cannulated screw group. This was consistent with results from prior biomechanical studies[19] and is not surprising given the greater surface area of the needle injection method over which the cement can bond to the bone, as opposed to the few sites of fenestration in the cannulated screw method. Operative time was much shorter and complications like cement leakage were lower in the cannulated pedicle screw group. But needle injection appears to be more effective and cheaper.

3. Dual independent construction with four-rod technique

One of the most formidable obstacles to successful spine surgery is pseudarthrosis which is a failure of fusion of the intended osseous elements. There is an arms race that takes

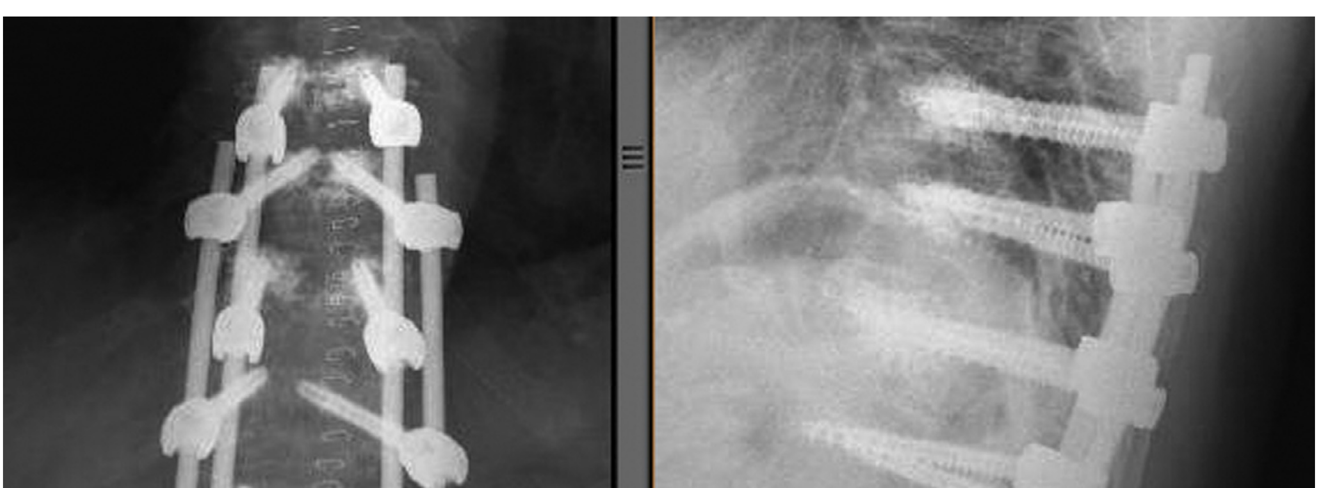

Fig. 1 – Cement augmentation using fenestrated pedicle screws. AP and lateral X-ray.

place between the biological process of fusion that must create biological stability prior to mechanical failure of the metal construct implanted at the time of surgery. The latter is an attritional process of gradual overload cycling to biomechanical failure of the metal components. If biological fusion is delayed beyond the metallic phase's *in vivo* lifespan, failure ensues. This manifests on X-ray as rod fracture and screw pull out and is confirmed on CT by absence of bridging bone between the desired segments. We call this clinical scenario pseudarthrosis[20] and it is one of the most common indications for revision surgery. A solution to this problem is the installation of independent suspensory systems each bearing a smaller portion of the whole mechanical load than the sum of their parts. Quad- or multi-rod constructs have been shown to decrease the rates of instrument failure and symptomatic pseudarthrosis when compared with traditional dual-rod constructs.[21,22]

Shen et al. discuss the technical considerations that must be taken into account when placing a long segment dual construction with four-rod techqniue.[23] They recommend two biomechanically independent but functionally complementary fixation systems. In order to achieve this, they use two different pedicle screw trajectories at alternating odd or even segments. The Roy-Camille or "medial" trajectory derives its start point from the intersection of horizontal and longitudinal lines that bisect the transverse process and facet joint, respectively. The Roy-Camille screw is then inserted in as much a direct A-to-P direction as pedicle anatomy allows while paralleling the vertebral endplate at that level.[24] The Magerl or "lateral" screw uses the same horizontal line that bisects the transverse process but a more lateral starting point at the lateral border of the superior articular facet.[25] The Magerl screw is angled with more acute medialization than the typical anatomical pedicle screw and similarly parallels the endplate in the cranial-caudal dimension. The lateral screws are connected by an independent long segment rod between their tulip heads. The medial screws are connected by a second independent rod between their heads, forming two separate suspensory systems, or a "quad rod" construct. Distal fixation is created by the use of 4 divergent pelvic screws that are placed in a Galveston-like technique by using the posterior superior iliac spine as the starting point and following the triangular column of bone above the acetabulum toward the anterior inferior iliac spine.[26] The proximal iliac wing screw placement is more variable and dependent on the position of the lumbar screws and rods. The starting point for the four pelvic screws should be recessed by removing a portion of the bone where the anchors will lie so as to decrease the prominence of the screw heads. By having two screws in each ilium, a distal foundation of four bony anchors is created. By alternating medial and lateral screws at each level and then mirroring the left and right side Shen et al. fashion a distinct "Christmas-tree" appearance to the final construct. Clinic X-rays appear replete with ornaments (screw heads) and 3-dimensionality (Fig. 2). The construct has been shown to have the highest pullout strength with no known systemic failures. Finally, the most proximal bony anchor should be a lateral screw, they recommend, in order to decrease the risk of rod impingement on the superior facet joint and to avoid destabilizing the supra-jacent juxta-fusional level.

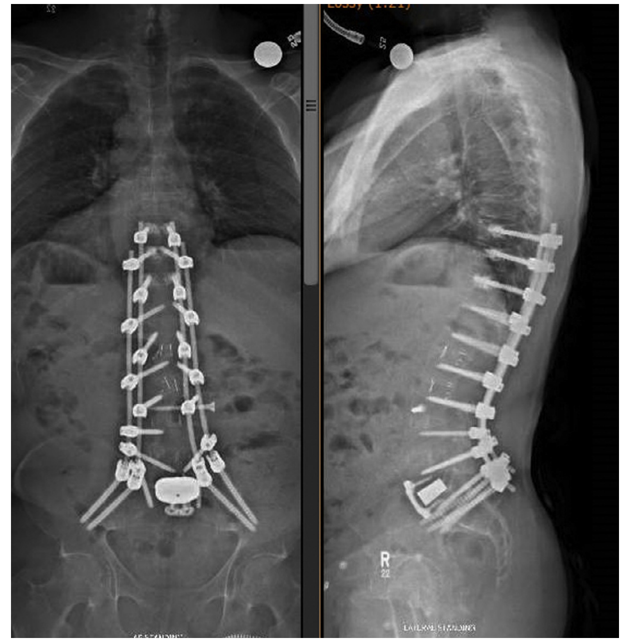

Fig. 2 – Dural independent construction. AP and Lateral X-ray. Note: the alternating Roy-Camille (anterior to posterior) and Magerl (medializing) screw trajectories.

4. Multi-rod constructs

Palumbo et al.[27] provide an alternate description of multi-rod constructs. In Palumbo's version the outrigger rods are shorter "satellite" rods installed to support the long-segment construct. Palumbo et al. detail important considerations regarding rod contouring and implantation order. First, the two primary rods are cut to the desired length and then contoured to avoid stress-risers from sharp angular bends. These rods are placed within the screw heads and set screws tightened. Maneuvers to correct deformity, such as global de-rotation or cantilever bending are performed using these two primary rods. The satellite rods then reinforce and lock-in this desired position once it has been attained by the primary rods. In addition, they recommend decortication, irrigation and bone grafting prior to placement of the outrigger rods as they may obscure the fusion surfaces. According to Palumbo the rods do not have to be equal in length and should only span the segments most at risk for non-union or failure. Based on the anatomic characteristics of the patient and desired area for bone graft placement, the supplemental rods can be placed either medial or lateral to the primary rods. Next, both the cranial and caudal ends of the outrigger rods should be connected to the primary rod using side-to-side connectors with additional connectors added at intermediate points depending on satellite rod length. In cases where deformity or prior surgery results in difficulty placing the primary rod into a screw head, selected screws can be skipped by the primary rod and captured with the outrigger rod. Placement of a standard iliac bolt and sacral pedicle screw allows enough medial-lateral distance for a side-to-side connector between the primary rod engaging the iliac screw and the ipsilateral outrigger rod engaging the sacral screw.

Additionally, the placement of an S2 alar iliac (S2AI) screw can allow the primary rod to engage both the S1 and S2 fixation sites if desired. The midline of the outrigger rods and portions of the primary rods that extend beyond the outrigger rods are then crosslinked. Excessive crosslinking should be viewed with circumspection for its recent association with increased pseudarthrosis rate, likely the result of construct over-rigidity and constraint of physiologic micro-motion. Where neither a true quad rod construct nor dual outriggers are desired, a single supplementary rod can be contoured to fit a unilateral short segment for reinforcement and connected to the primary construct with side-to-side connectors as needed.

Although counterintuitive, the evidence has demonstrated that multi-rod constructs have no disadvantage to the traditional dual-rod constructs in estimated blood loss or operative time. Moreover, the decreased rate of fixation failure or rod fracture[21,28] portends improved symptomatic outcomes and decreased cost associated with revision. Interestingly, four-rod constructs have demonstrated measurable improvement in stability over traditional two-rod constructs in flexion, extension, and, with the addition of cross-links, in left-right axial rotation.[29] These results suggest that multi-rod constructs can be used to increase stability and decrease complications in patients who require revision spinal surgery.

5. Dural scar resection

The end result of the multiply revised thecal sac is the accumulation a thick rind of scar tissue that overlies the dura and may be several centimeters in depth. This scar blurs the line between true dura and overlying tissue such that a plane in the epidural space may no longer exist.

Surgeons have questioned whether this accumulated scar tissue is compressive or restrictive, or whether it contributes to symptomatology at all. Is the painstaking task of dural scar resection down to native dura worth the near inevitability of incurring occasional dural tears, cerebrospinal fluid leak and prolonged head of bed restrictions with the possibility of late sequelae such as pseudomeningocele and superinfection? The answer is ‘yes’, but the value of scar resection to the patient depends on the surgeon’s familiarity and proficiency with this technique.

Youmans and Winn Neurological Surgery describes the surgical technique for revision dural scar resection.[30] In general, the surgical exposure should be extended beyond the margins of the prior incision so that the surgeon can work from normal anatomy to the altered anatomy, identifying intact tissue planes (eg: dura) and following them back to identify and tease scar away from important structures. The procedure starts with sharp dissection through skin, fat, fascia, and muscle down to the epidural space near the previous laminotomy site. Bony landmarks are palpated through the tissue prior to approaching lamina defects (as noted on pre-operative CT) and normal bone close to the target level is exposed taking care not to violate facet capsules that may lay beyond the intended fusion mass. At the scarred level the bony margins of the laminectomy are cleared using high pressure angled curettes pulling away from the canal, scraping scar off the bony edges. This type of sharp dissection reduces the risk of tears propagating into the dura from adhered soft tissue. When the edges are exposed the lamina can be thinned with use of a high speed pneumatic burr as needed and then a Kerrison rongeur used to expand the laminectomy sites. Continue this until normal dura is identified and stenosis is relieved by feeling with a ball tipped probe along the central and sub-articular zones as well as along the foraminal paths of the exiting and traversing nerve roots for each level. Once exposure is complete a straight black-handled magnum curette can be stabilized on the patients skin overlying the paraspinal muscles and used to scrape in a caudal to cranial angular motion along the length of the thecal sac pulling scar tissue up and off the dura along its naturally occurring plane of dissection. Though effective this technique does come with risks of durotomy. By working from normal areas to those covered in scar tissue this risk can be mitigated.[31] A 15 blade scalpel can be used when a thick adhesive band is encountered between epidural scar and the dura itself. With the knife blade oriented away from the canal, a firm, steady motion of the knife can release the adhesion. Finally if primary repair with suture or dural graft is inadequate because of anterior or inaccessible leak a lumbar subarachnoid drain can be placed to decompress the thecal sac and allow healing.

6. Proximal junctional kyphosis (PJK) prevention techniques

Correction of deformity is good, but over-correction can lead to construct failure and recurrent sagittal imbalance. Previously defined parameters may not work in a “one size fits all” fashion. In fact, each demographic can tolerate variable population-specific levels of rigidity and correction given their defined ideal parameters. Often, if not balanced appropriately, the spine or the construct may respond with failure if too stringent a correction is exacted upon it. After decades of degenerative adult deformity and loss of mineral density it is unrealistic to expect octogenarian soft tissues, muscular biomechanics and habitual postures to adapt to the strict parameters of sagittal or coronal correction defined by adolescent idiopathic scoliosis (AIS) ideals, for example. The former is far more apt to fail proximal to the construct where soft tissues and the remaining “unfixed” elements of the skeleton revert back to their degenerative baseline position under pressure from learned ergonomic patterns of pre-operative functioning and gait. AIS on the other hand can accommodate large corrections with growth and muscular / postural adaptation to a “new normal”, allowing biological and behavioral acceptance around the new surgical construct. Ideal correction parameters must be calibrated with nuance based on body type and patient demographics. Demographic-specific ideal correction parameters must still be defined. Until then, the head surgeon’s discretion is invaluable in determining the precise mix of factors that optimize patient correction for symptomatic relief while ensuring longevity of the surgical construct and minimizing the risk of PJK.

Life is a kyphosing event and many factors beyond the degree of surgical correction can influence the pathogenesis of PJK. These include pre-operative factors such as age, bone health, muscle mass, and activities. Intra-operative considerations are important as well such as construct rigidity, number and highest level of fixation points, number and type of rods (titanium vs cobalt chrome), stress transition techniques (screw vs hooks at highest level), posterior tension band preservation during exposure and supra-spinous ligament (SSL) reconstruction techniques (with allograft or mersilene tape).

Where pedicle anatomy does not accommodate a screw, laminar screws can be adapted allowing firm osseous purchase in a dysplastic or “swiss-cheesed” segment. Moreover, because they are not intra-osseous, laminar hooks are a less rigid form of stabilization. Laminar hooks can provide a natural stress transition easing the rigidity between fully instrumented long screws penetrating over 75% of the body depth and proximal more physiologically mobile uninstrumented juxta-fusional levels. Laminar screws are placed at a near horizontal angle driven between the inner and outer tables of the lamina in a unilateral fashion staying always posterior to the neural elements. Though they produce an alarming optical illusion on PA X-ray (the illusion of intra-canal instrumentation) they importantly have valuable application in levels with anterior and middle column osseous deficiency where segmental stabilization is required by exploiting the retained bone stock of the posterior elements to achieve fixation. The deformity surgeon may consider terminating the superior most instrumented segment with either of these techniques (laminar hooks vs screws) as dictated by the osseous anatomy and availability depending on the desire to ease stress transition or augment segmental stability.

Post-operative modalities are also important, such as physical therapy or voluntary postural control and behavior modification. Although a rigid spinal construct results in increased stability and allows more ambitious sagittal correction and safer derotation, the consequences involve steep alterations in motion segment biomechanics at stress transition levels. The unfused facet joints above the construct compensate for lost motion and subsume the brunt of concentrated strain where the patient knowingly or unconsciously attempts to re-establish a proprioceptive sense of normalcy with their activities of daily living. Over time this can lead to PJK.

PJK is a pathologic kyphotic deformity that occurs at the most proximal extent of a construct. Obvious risk factors for developing PJK include procedures or implants that increase the rigidity of the spine such as fusion and the use of pedicle instrumentation.[6,32] The popularization of pedicle instrumentation revolutionized the scope and efficacy of spine surgery and allowed robust osseous fixation and reliable regional manipulation beyond what was possible with hooks or sublaminar wires previously. In the wake of technological innovation the increased length, strength, and correction of constructs brought with it unforeseen long-term sequelae. PJK has an incidence of 6–41% after spinal fusion[33,34] and unfortunately requires sequential extension of the surgical construct in patients who kyphos over their exiting fixation every 2–5 years. PJK is therefore the bane of many good interventions and an area of ongoing research for preventative techniques. To this end, various techniques have been described in the literature, each with its own advantages and drawbacks. These include: weaving mersilene tape or cadaver tendons through spinous processes to reconstruct the SSL, dynamic stabilization technologies and cement augmentation.

Safaee et al.[35] have demonstrated their preferred intra-operative techniques for PJK prevention and also filmed a video enhanced guide depicting their execution. Regarding exposure for example, they describe the following order of steps: the patient is positioned prone on a spine Jackson table and prepped and draped in the usual sterile fashion. Fluoroscopy is used to confirm the appropriate level and the proximal most extent of the incision is marked extending directly superficial from the vertebral body immediately below the uppermost instrumented vertebrae (UIV-1). Thereby the dissection spares the soft tissues immediately proximal to the construct. The incision is carried from here down to the pelvis. The spinous processes, lamina, facet joints, and transverse processes (TP) are then dissected out laterally in a subperiosteal fashion. The Midas Rex bur (Medtronic, Dublin, Ireland) is used to mark and deepen the starting points for pedicle screw insertion. The trajectories are then created by cannulating the pedicles with a gearshift lenke probe, followed by sequential palpation, tapping, and re-palpation to ensure no cortical breaches and an intact anterior vertebral body cortex. Pedicle screws are then placed at all levels except for the UIV and UIV-1 levels where pedicle markers are left in place after cannulation. Intraoperative computed tomography is then used to confirm screw position and osseous purchase without medial/lateral or foraminal breach. Once satisfied that the proximal soft-tissue preserving technique has allowed adequate exposure to achieve appropriate position of proximal pedicle cannulation, the final screws can be placed at the UIV and UIV-1 levels ensuring an intact soft tissue envelop and no disruption of native continuity of the posterior soft tissue tension band. This is thought to assist in the prevention of PJK.

Safaee et al. further recommend cement augmentation at the UIV levels for prevention of PJK. After decorticating the pedicle entry points and tapping and measuring the cannulated sites they describe inserting a syringe injectable thrombin-containing hemostatic agent (Floseal, Surgiflo, etc) deep into the pedicle tract to occlude venous channels. Next, they recommend injecting 3ml of liquid PMMA into each pedicle tract followed immediately by final screw placement for the UIV level only, skipping UIV-1 to allow for increased flexibility at the top of the construct. Cementation they aver assists in the prevention of PJK from a fracture etiology which is typically observed in the thoracolumbar region. Therefore the authors recommended cementation for instances where the top of the construct terminates within the thoracolumbar junction (T12-L1). PJK in the upper thoracic spine is believed to more commonly result from ligamentous failure and therefore may not benefit from cementation.

For constructs terminating higher up in the thoracic spine, Safaee et al describe the use of hook fixation. After executing the soft tissue sparing exposure technique described above they placed transverse process hooks instead of pedicle screws at UIV. This method allows for a softer stress transition at the UIV level while also obviating the need for extensive dissection. Hooks can be applied underneath muscle and around transverse process without subperiosteal exposure allowing preservation of the soft tissues. Evidence supports this notion, published by Hassanzadeh et al.[36] who performed a comparative study between transverse process hooks and pedicle screws at the UIV level of 47 patients and found that patients with pedicle screw instrumentation had a higher prevalence of PJK. Kim et al. and Helgeson et al. further conducted large scale studies with similar results suggesting that a dynamic hybrid construct consisting of hooks, instead of a rigid rod-screw construct, was effective in preventing PJK.[6,37]

Ligament augmentation can then be performed at UIV-1, UIV, and UIV+1 levels to reinforce the posterior tension band. A matchstick burr is used to drill a through-and-through hole in the center of each spinous process at these levels. Next a sub-laminar cable is looped through these holes in a mirrored interweaving fashion. Pre-setting of the desired level of tension is performed by pulling the cable taut on each side by hand. Finally, the cable is fixed to the rod while holding this tension using commercially available connectors. The spinous processes at these levels are held in gentle extension in order to potentiate elastic resistance to flexion when the patient is upright. A recent study conducted by Safaee et al.[38] provided data demonstrating a significant decrease in PJK with this technique of ligament augmentation at a mean of 12 months follow-up.

Kebaish et al.[39] performed a biomechanical cadaver study that examined prophylactic vertebral cement augmentation to reduce the risk of proximal junctional fractures (PJF), a progression of disease in the PJK spectrum, in patients with osteoporosis. They found that augmentation at the UIV and UIV+1 levels resulted in reduced incidence of proximal junctional fractures. They also noted that augmentation at the UIV level alone provides no additional benefit. Similarly, a clinical study conducted by Hart et al.[40] found that prophylactic vertebroplasty of either two or three adjacent cranial vertebrae was effective in preventing proximal junctional acute collapse. Based on this, it can be concluded that the use of prophylactic vertebral cement augmentation can be preventative in the development of proximal junctional kyphosis.[41] In addition to demonstrating efficacy of PJK prevention through prophylactic vertebroplasty, Hart et al. also found that prophylactic vertebroplasty was a more cost-effective procedure as compared with revision surgery.[40] This is not surprising given the burgeoning costs of OR time and hospital stays and it underscores the importance of technical knowledge and proficiency with preventative techniques. Finally, the advantage of a vertebroplasty-enhanced construct is dependent upon underlying bone mineral density in the first place and should be reserved for osteoporotic bone or patients at highest risk for fracture.[42]

Various techniques of posterior tension band reconstruction and SSL augmentation have been described. Zaghloul et al.[43] describe the use of mersilene tape which they build into a check-rein strap for posterior stabilization of the proximal junction of fusion constructs. After exposure and pedicle screw placement, a 5-mm mersilene suture is used to either connect the proximal screws or cross-link the screws to the spinous process above the last instrumented vertebra (Fig. 3). The suture is passed proximal to the adjacent level spinous process (SP), making sure to stay deep to the supraspinous and interspinous ligaments (ISL). It is then looped distal to the SP creating a tensioned 360° loop around the adjacent SP with each pass. Alternatively, drill holes can be made in the spinous process to facilitate passage of the suture. The tape is then passed under the rod on each side and the ends are tied under tension over the rods or a cross-link in order to create a functional posterior tension band.

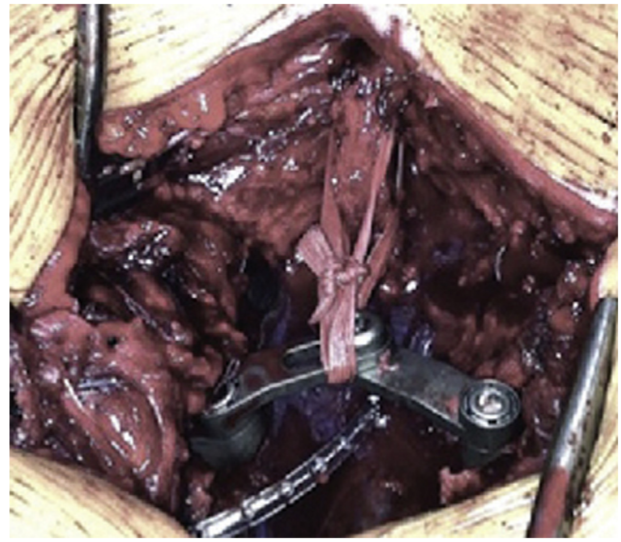

Fig. 3 – Posterior tension band reconstruction with 5mm mersilene tape tied around supra-jacent spinous process and anchored under tension around crosslinked rods.

Pham et al.[44] described a similar strategy using allograft. They select a cadaveric semitendinosus tendon allograft which they secure using a looped number 2 Ethibond suture sewn in a modified running locking Krackow fashion for augmentation of the ISL. They soak the semitendinosus allograft in antibiotic solution to assist with prophylactic infection control. In detail, they describe that an assistant stabilizes the tendon at both ends by pulling it taut with both hands. The suture needle is passed through the center of the tendon while the double filament loop is passed over the end and cinched down in luggage tag fashion capturing large bites of the tendon substance in its loops. This anchors the weave. The needle is then sequentially passed through the center of the tendon again and again with the Ethibond loop being passed around the end of the tendon each time progressing stepwise down its length until the sutures are passed out of the end of the tendon graft longitudinally at the final pass. The tendon is then flipped and the process repeated starting at the center progressing down the contralateral leg of the graft. Finally, the tendon is intervoven between the spinous processes from the UIV+1 to UIV−1 or UIV−2 levels for optimal tensioning. The UIV+1 spinous process is captured by the needle without direct visualization as it is not dissected out and still retains its soft tissue covering. This means that the transosseous bite must be made under supra-fascial palpation in a ligament preserving technique. This ensures there is no disruption of the soft tissue or ligamentous attachments at UIV+1. Next, small paramedian openings are made in the fascia bilaterally in order to pass the graft through the interspinous space and then inferiorly down to the spinous process at the UIV level and below. The graft is intervoven between the caudal SP's under gentle tension until only the free ends of the suture remain and are then tied together. Four patients underwent this procedure by Pham et al. with mean radiographic follow-up of 5.5 months and were found to have no radiographic evidence of PJK within that, albeit short, time-frame. However, Yagi et al. found that 66% of PJK occurs within 3 months of the immediate post-operative period and 80% occurs within 18 months of surgery[45] indicating that if the biomechanical milieu is going to eventuate in PJK it does so relatively rapidly. Therefore, although the methods described by Pham et al. require longer follow-up and larger sample sizes to be conclusive, the preliminary results are a good foray into devising a much needed solution for a difficult problem.

The techniques mentioned here are intuitively and empirically safe as they involve minimal foreign body biomass, run only minor risks associated with viral communication or immunogenicity if allograft tendon is selected, and advocate more conscientious and meticulous dissecting habits above all. Definitive consensus on PJK reduction will likely remain elusive until more powerful or more ingenuitive methods are devised. In the meantime, techniques such as vertebroplasty and ligament augmentation have been shown to be cost-effective and deserve our efforts while we continue to labor to drive down the incidence of PJK.[40,46] Long-term data and clinical trials in addition to further technological innovation are likely to remain critical areas of research.

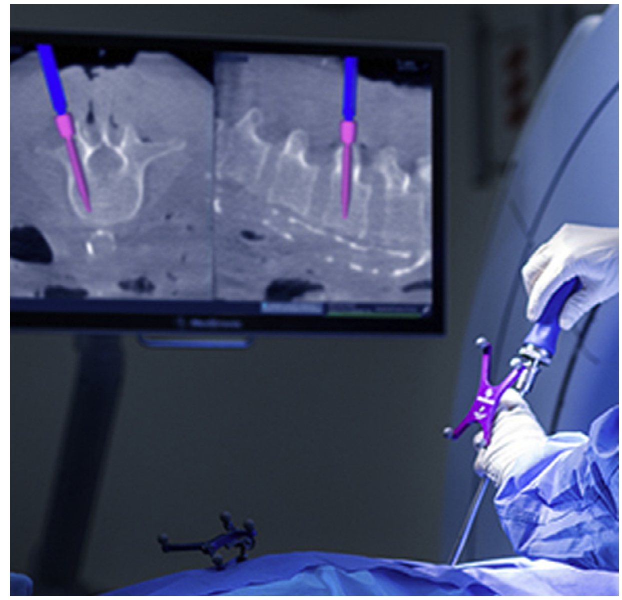

Fig. 4 – Axial and sagittal 3D renderings of osseous anatomy with real-time representations of on-field navigated instruments allows precision visualization and planning of screw trajectories.

7. Navigation and robot assisted surgery

Distorted anatomy from previous decompression or fusion always makes revision surgery difficulty for free-hand pedicle screw placement. 3D intra-operative computed tomography (CT) guided robot delivered pedicle screw placement plays an important role in safely instrumenting highly irregular, deformed spines or exuberant post-BMP2 fusion masses. These communicate in real time 3D multi-planar renderings that allow the surgeon to visualize and drill trajectories with robot arms and deliver screws with enhanced precision (Fig. 4). Advantages are less X-ray use and radiation exposure to the surgical staff, less aberrant screw placement with possibly less neurologic injury to roots, cauda, or cord, potentially faster and more effective screw placement. Drawbacks include possible increased radiation exposure for the patient via multiple spins of the CT scanner for long segment fixation, cost of navigation and robotic equipment to hospitals, possible prolonged pre-operative set up and scanning time, and possible catastrophic screw placement with inadvertent discoordination of the sensor probe away from the patient's true anatomic position.

Theologis et al.[47] describe their experience with Stealth navigation technology (Medtronic inc., Dublin, Ireland) used for pedicle screw placement in 13 revision spine surgeries. After O-arm spin, the surgeon can drill, tap and place pedicle screws with real time visualization of the instrument in a 3D representation of the osseous corridor (Fig. 4) while the reference array and navigated instruments are detected by the Stealth optical camera. Trajectories of each screw are visualized on the Stealth Station's axial and sagittal images prior to final screw placement and screw location is confirmed by intraoperative O-arm. Similar techniques are described in both the adult and pediatric populations.[48–50]

SpineAssist, or the Mazor robot (Medtronic inc. Dublin, Ireland) intra-operative workflow is described by Devito et al.[51] Pre-operative CT scans are acquired to determine ideal dimensions and optimal position of all implants. Intra-operatively, a mounting frame is attached to the patient's spine and targets for image registration are connected to the frame. Image acquisition and registration simply requires one intra-operative AP and lateral fluoroscopic view which automatically correlates the current position of the patient to known osseous anatomical positions on the basis of pre-operative CT data. The robot is then mounted to the frame and locked into position. A guiding tube on the robot arm then aligns itself with the anticipated trajectory of the screw. The pedicle tract is percutaneously prepared by using the drilling tube as a template for guided cannulation or a standard open approach can be utilized. Similar surgical techniques for use of robot assisted surgery have been described by other authors.[52,53]

The amount of radiation exposure to the patient and OR staff when comparing 2D fluoroscopy to 3D navigation has been examined and reported. Although some studies have shown that the total duration and effective dose of radiation to the patient is less when using 3D navigation,[54,55] more recent studies have shown that patient experiences a greater amount of radiation exposure with the use of 3D navigation techniques[56] whereas staff experience much less to no radiation. Whereas patients may have few lifetime exposures, surgeons and OR staff who perform many surgeries per week for decades have demonstrably higher rates of cataract surgery and may develop cancers from chronic exposure. This is an important consideration for revision surgeons to bear in mind when making professional and ergonomic decisions for their imaging modalities as well for hospitals, insurers and healthcare policy makers when managing the health of employees and providers.

8. Conclusion

As population age and comorbidities increase and the incidence of primary spine surgeries continues to rise the demand and complexity of associated revision spine surgery will likewise continue to grow.[57,58] What a surgeon should do in these situations depends on what a surgeon can do. Knowledge and proficiency with vast technical expertise is the last line of defense for many of these patients if we are to alleviate the clinical and economic scourge of failed spine surgery.

Disclosure

The authors report no proprietary or commercial interest in any product mentioned or concept discussed in this article

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