Posterior segmental spinal fixation in Scoliosis surgery

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Posterior segmental spinal fixation in Scoliosis surgery

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Introduction

Spinal deformity was recognised in the ancient works of philosophy, religion, myths, and fairy tales dating back as far as 3500 BC\textsuperscript{1,6}. Scoliosis was first described in the 5\textsuperscript{th} century BC by Hippocrates. He recommended treatment with axial distraction on an extension apparatus (figure 1).

Galen coined the term “Scoliosis” in the second century AD to define the frontal plane curvature of the spine, and kyphosis likewise to describe a sagittal plane deformity. In addition to axial distraction, he tried various chest binders and jackets in an effort to control the curves. He further advocated singing and respiratory exercises to correct the thoracic distortion. During the Dark Ages, scoliosis was seen as divine retribution, common amongst heretics and treated with the “rack”.

Venel in 1780 founded the first hospital specialising in skeletal deformity. In addition to a traction bed, he developed a brace, which applied horizontal forces attempting to derotate the spine, as well as extension forces.

The first surgical reports date from the latter 19\textsuperscript{th} century. Guerin in 1839 used percutaneous myotomies of the vertebral musculature, in conjunction with bracing. He was subsequently banned from practice in France, returning to Belgium after investigation by Malgaigne who wrote “It is important to know what to do but no less important to know what not to do”.

Volkman performed rib resections in 1889, the first bony surgery for scoliosis. Sayre popularised plaster of Paris casts applied while the patient was in a vertical suspension device.

Spinal fusion was first performed in patients with tuberculosis. In 1902, Lange used rods anchored to the spinous processes in an attempt to control kyphosis. In 1911, Albee described spinal fusion for Pott’s disease of the spine using tibial autograft.
In 1924, Hibbs\(^2\) reported on 59 cases of spinal fusion for scoliosis. He utilised post-operative cast bracing for 6 to 12 months. Others also performed fusions, but reported pseudoarthrosis rates of up to 60\%\(^1\). Techniques were refined with Moe identifying the need for meticulous detail in facet fusion, thorough decortication and addition of autologous bone graft. This resulted in failed fusions falling from 65\% to 14\%\(^1\).
History of spinal instrumentation\textsuperscript{3-19}

1\textsuperscript{st} generation: Harrington distraction instrumentation\textsuperscript{4,7}

Paul Harrington revolutionised deformity surgery in the 1960's with the introduction of his instrumentation. Previously surgeons had relied on the use of external methods to control the spine after fusion. The internal instrumentation allowed the corrective forces to be applied directly to the spine. Allan\textsuperscript{3} reported on the use of his device (figure 2) in 1955. He used distraction in the concavity by means of transverse process attachment. Due to its attachment principles correction was limited to partial correction of severe curves, and reported that curves less than 70 degrees should be treated by other means.

Figure 2: Allan’s Device using distraction between the transverse processes in severe curves.

Harrington's device was originally devised for use in the treatment of neuromuscular scoliosis (poliomyelitis). Despite marked deformity correction, they failed in the early post-operative period. Moe combined the use of the rod with fusion, and despite achieving similar correction to his uninstrumented patients, there was a marked benefit in the post-operative period. Patients usually in bed for up to 10 months were now mobilised in days. This technique became the standard and was used in many areas of spinal surgery.

However, it only addressed one plane of deformity, viz. the coronal plane. Also it relied on distraction as the principal corrective force, and with distraction between two points there was the problem of straightening the spine in the sagittal plane, giving rise to the so-called 'flat back' syndrome. This was due to the loss of, or failure to reconstitute the normal sagittal profile of thoracic kyphosis and lumbar lordosis. The Harrington rods were modified by Moe, from round ended to square ended to make them rotationally stable in an effort to allow sagittal contouring of the rod, and prevent rotation of the rod when fastened to the spine. However, you were still left
with distraction of two points, which has a tendency to flatten the sagittal profile as illustrated in figure 3.

Although Harrington is well known for the distraction rod, he used an additional compression rod from the 1960's. This was applied on the convexity and Harrington reported improved correction of the Cobb angle in the coronal plane. Despite this, many surgeons used only the distraction rod. Gaines\(^9\) explains this disuse on the surgeons' experience and lack of documented evidence proving the particular values of the compression system. He reported on the benefits of improved thoracic and lumbar sagittal profile, as well as an improved tilt angle correction on the coronal plane when using the compression system. Gaines\(^{10}\) also reported on improved rib hump correction using the compression system.

2\(^{nd}\) generation: Segmental fixation.

In an attempt to address the problem of sagittal profile, segmental fixation developed. This involved fixation to multiple vertebral levels. Luque\(^{11}\) introduced this principle with sublaminar wires and L-shaped rods, but for another reason. His Mexican patients were poor and the climate made brace wear difficult. He thought segmental wiring would strengthen the construct and could therefore dispense with the brace. There were initial failures, until fusion was combined with his technique.
With sublaminar wiring, neurological injury was introduced, a much higher incidence than with previous techniques. Luque\textsuperscript{11} reported 7 transient parasthaesias in 78 patients. Two further patients had post-operative muscle weakness. Wilber\textsuperscript{12} reported on 137 cases undergoing posterior fusion for scoliosis. There was a 17% neurological complication rate in the segmental sublaminar cases as opposed to 1.5% in the Harrington group. Of the 17%, 4% were a major injury to the cord with 13% being transient sensory changes. This concern led to alternative wiring techniques, using the base of the spinous process, however the fixation was not as strong. This segmental wiring was adapted to become the Harrington-Luque method, where sublaminar wires were applied to a pre-bent Harrington rod. This not only allowed the sagittal plane to be corrected, but also attempted to derotate the spine by pulling the lamina to the rod, using translation rather than distraction as a primary corrective technique. Unfortunately, the sublaminar wire adopts its own position around the lamina, and in severely rotated curves may translate the spine to the rod without derotating. The rib hump may in fact become more prominent, leading to a poor cosmetic result.

The use of the Harrington rod has proved extremely effective with relatively low complication rates. Youngman and Edgar\textsuperscript{15} reported on 319 cases over an 8-year period. Their methods evolved during this period from correction pre-operatively in a Risser turnbuckle cast (21 cases), to a period of Cotrel traction and plaster jacket (64 cases) to all correction being performed intra-operatively. Most of their cases had simple Harrington distraction rods (287), with 19 cases having an additional transverse bar pulling the apex across. In 13 cases segmental sublaminar wires were used.

Their average pre-operative Cobb angle was corrected from 65.5° to 32.1°, a coronal correction of 51%.

Complications occurred in 25 (8%) of the patients. There were 4 deep infections in the early post-operative period. These all occurred in patients who did not receive prophylactic antibiotics, as was the protocol for a short period of the study. There were a further 2 late infections, bringing the total infection rate to 1.8%. 3 of the 4 early infections were associated with hook dislodgement. There were a total of 8 hook dislodgements (2.5%).
There were pneumothoraces in 2.8% and a 1.9% pseudoarthrosis rate. Superior Mesenteric syndrome (Cast syndrome) occurred in 1.9%.

They had transient neurological impairment in 0.6%. Both were identified on SSEP. One resulted in a Brown-Sequard syndrome with subsequent improvement and only residual dysthaesia of the lower limb. The other case was unable to move her legs post-operatively and the Harrington instrumentation was removed with subsequent complete recovery.

Mielke, Lonstein et al\textsuperscript{16} reviewed 352 patients over 24 years, with the vast majority (230 patients) having simple Harrington distraction rods. They reported a slightly lower percentage correction of 42%, and a higher complication rate. Twenty-three percent of these patients had complications. There was one death due to gastric perforation secondary to vascular obstruction of the duodenum. There was a 3.1% pseudoarthrosis rate, lower in the segmental sublaminar wire group (2.3%) and higher in those not immobilised (8%). They had similar infection rates, and only minor neurological problems.

Thompson et al\textsuperscript{18} compared Harrington instrumentation using segmental wiring and Luque instrumentation in idiopathic scoliosis. They found the correction to be similar at 46% and 48% respectively. They had neurological complication rate of 15% and 20%, with serious compromise in 3% and 5% respectively. There was near complete recovery in all, except one case with residual mild hemiparesis. The neurological complications occurred early in the series, and the authors felt there was a definite learning curve. This is supported by the fact there was no serious neurological injury in the last 99 cases. They found no differences in the complication profiles between the Harrington-Luque and Luque groups. They concluded that neurological injury was associated with the surgeon’s experience with the sublaminar technique.

**3\textsuperscript{rd} generation: Cotrel Dubousset instrumentation (CDI).**

In the 1980’s, Cotrel and Dubousset introduced the third generation of spinal instrumentation. They added the concept of derotation using powerful segmental fixation, following on from the derotation achieved with the anterior devices such as
Dwyer and Zielke in the thoracolumbar area. CDI enhanced pedicle fixation by designing specialised hooks and pedicle screws. This provided a stronger lever arm on the spine to effect this derotation manoeuvre. Transverse traction was employed to pull the apex of the curve towards the concavity. To support the apex a device for transverse traction was designed, i.e. the cross-link. The cross-link increased stability by converting the two parallel rods into a quadrilateral construct. This eliminated the potential for the rods to slide on each other in the frontal plane and to rotate about each other in the sagittal plane.

Fitch et al.\textsuperscript{22} compared 32 CDI cases with 30 Harrington-Luque cases of idiopathic scoliosis retrospectively. The CDI group had a correction of 68% compared to the Harrington-Luque’s 52.8%. The CDI had less loss of correction, at 1.8° and 8.1° respectively. CDI produced a 58% correction in the thoracic kyphosis, with Harrington Luque 30%. CDI was found to correct the rib hump by 6° when measured with a scoliometer whereas the Harrington-Luque had minimal effect.

Humke et al.\textsuperscript{23} compared 72 idiopathic scoliosis cases undergoing Harrington instrumentation (with a distraction rod plus a compression rod on the convexity) and CDI. The CDI correction was 66.3%, with the HI 51%. The average loss of correction was 5% compared to 20.7%. The change in rib hump height change was the same at 36%. 10% of the HI group complained of severe back pain, whereas only 1(5%) of CDI complained, although he used no analgesics.

\textbf{Corrective manoeuvre}\textsuperscript{24-29}

As instrumentation changed, so did the techniques of correction. Earlier techniques used pure distraction, but there is concern regarding injury if the distractive force is transmitted to the cord. CDI introduced a derotation manoeuvre once the rod was attached to the spine, whereas the newer systems such as Colorado and the Universal Spinal System (USS) utilise powerful instrumentation to translate the spine to the rod.
There has been criticism of the CD derotation manoeuvre causing decompensation of spinal balance. Also the CDI claims of derotation of the spine (as opposed to rod derotation) has been challenged.

CDI is reported to achieve active derotation of scoliosis by changing the curve from relative lordosis to kyphosis, producing a rotational force opposite that of the initial deformity, which is then augmented by the insertion of the convex rod. Derotation from 14 to 40% has been reported. Various amounts of en bloc rotation of the whole spine has been found to occur, in addition to significant intersegmental rotation (uncoupling) at the cervicothoracic and thoracolumbar junctions.

Wood et al. using CT imaging found that CDI did not consistently derotate the thoracic apex relative to the pelvis. King 2 curves derotated well, and may be better suited to absorb the transmitted rotational forces. King 3 with more rigid segments did not derotate.

Delorme et al. compared the CDI with the Colorado systems where derotation was used in the CDI group and translation in the Colorado group. They were unable to observe a clinically relevant apical derotation in either group. They suggested the en bloc derotation, which was challenged by Tredwell.

The difference in reports regarding the derotation may be due to the focus being on apical derotation in the horizontal plane, rather than total curve derotation. Tredwell et al. performed a prospective study using intraoperative stereophotogrammetry to analyse helical motion of the spine during the correction of scoliosis. They described the normal spine as two-dimensional, depicted by a sine wave with thoracic kyphosis and lumbar lordosis. They thought a scoliotic spine however represented a helix with translations and rotations in sagittal, coronal and horizontal planes. They found unique and individual movements at each vertebral level, and disputed the concept of en bloc movement. They defined a unique axis for each vertebra, and found that this was not isolated to the z-axis, as usually measured. There was a maximum translation on the x and y axis at the apex. They felt that the spine behaved like a derotating helix, with end vertebrae rotating in opposite directions, and the apex rotating very little. However in correcting the lateral curve to a more normal thoracic kyphosis, maximum translation of the apex occurred in the x and y planes. Most change was found to occur on the rod derotation. They concluded that posterior derotational
systems rotate the scoliotic helix and reposition the resultant sine wave toward the sagittal plane as described by the change in the plane of maximal deformity. Shufflebarger\textsuperscript{29} argued that a rod derotation manoeuvre essentially produces coronal translation and sagittal plane angulation. He calls this a cantilever manoeuvre. It does not cause apical derotation on its own, but requires the addition of the second rod with a differential bend.

4\textsuperscript{th} generation: Current systems.

Since the introduction of CDI, there has been an explosion in terms of fixation devices with different sized rods, various hooks and more recently pedicle screws. There has also been a movement to the use of titanium alloys to make the instrumentation Magnetic Resonance Imaging (MRI) compatible.

Presently, the accepted posterior instrumentation is that of dual rods fixed to the spine via multiple fixation points. The systems are modular allowing an assortment of various fixation devices including hooks that attach to the lamina, transverse processes or pedicles, and various sized pedicle screws. There are cross-bridges to increase the rigidity of the system.

Although there are many types of fixation devices, the mainstay of current practice are pedicle hooks and more recently pedicle screws. These pedicle hooks may be additionally secured by a locking screw or staple.

The current systems use a basic principle of segmental correction\textsuperscript{5,14}. The spine is freed, including complete facetectomies along the length of spine to be fused, with or without anterior release. It stabilises the spine by fixation at multiple strategic levels where each segment is corrected in three dimensions with respect to a reference point or foundation, in most cases the end vertebrae in the curve. By correcting and derotating each level, the rib hump is improved. Distraction is therefore avoided. The alignment of the spine to the sagittally placed rod allows the spine to find its own length. With versatile hooks/screws the spine is reduced to the rod, with segmental derotation rather than spinal-pelvic axis rotation\textsuperscript{14}.
Spinal cord monitoring\textsuperscript{20,21}

As the expectations of deformity correction increased, increased neurological risk was introduced. In an effort to identify a neurological event early, so as to be reversible, various methods have been employed.

The Wake-Up test has been the gold standard and is still in use as the definitive test to which other monitoring is compared against. The Wake-Up test was originally described in 1973 by Vauzelle. It measures gross motor function of both upper and lower limbs. It is a simple and inexpensive test, but runs the risk of anaesthetic complications such as endotracheal tube dislodgement and bronchospasm. It is also only confirms spinal cord function for an isolated moment in time and does not provide a monitoring function. It difficult to perform in retarded, deaf or very young patients.

The Ankle Clonus test was described by Hoppenfeld, but is ambiguous and its validity has not been confirmed.

Due to more aggressive spinal procedures and the problems with the above clinical tests, intraoperative neurophysiological monitoring has developed over the last few decades.

Initially the sensory pathways were stimulated using Somatosensory Evoked Potentials (SSEP). A peripheral nerve is stimulated, and the potential detected at the cephalic end. Cortical electrodes, C2 electrode, and epidural electrodes are commonly used. SSEP remain the most commonly used means of spinal cord monitoring. When performing posterior spinal surgery, the epidural electrode is easily placed and provides good traces.

Forbes et al\textsuperscript{29} reported on 1168 cases using Somatosensory evoked potentials in response to posterior tibial nerve stimulation. In their previous work they had identified that a 60% fall in the peak to peak amplitude conferred a tenfold increase risk of neurological complications, whilst about 25% of monitored patients experience a 10-50% drop.

Of their 1168 patients, 10.5% had greater than 50% loss of amplitude. A third of these had the trace rapidly re-established by electrode repositioning. Of the 84 patients with
persistent depression, included all but one of the 33 patients that suffered neurological
deficit. The one missed developed his peroneal muscle weakness on the third
postoperative day. There was a 100% correlation with the side of SSEP drop and the
side of the neurological deficit. The overall SSEP fall was 7.2% and neurological
complication 2.7%. There false negative rate was zero. There were 52 false positive
cases. The authors suggest they may have experienced mild reversible spinal cord
impairment, and therefore not true false positives.

Forbes et al.20 concluded that epidural SSEP monitoring is far more sensitive than the
Wake-up test and replaces it as in their series an abnormal Wake up test was always
associated with an abnormal SSEP.

There is a concern that an anterior cord injury may be missed if only SSEPs are used,
as they may remain normal, as shown experimentally. There are also a few case
reports of postoperative neurological deficits with normal SSEPs, although the injury
may have occurred after termination of monitoring.

To address this concern, newer techniques have and are being developed to monitor
the motor tracts.21,30 Stimulation is cephalically, either electrically or magnetically.
The distal function is monitored either by peripheral nerve response or muscle
activity. The anaesthetic agents have more influence on motor monitoring forcing a
change in anaesthetic technique. Also antidromic stimulation of the sensory pathways
must be excluded to confirm true motor monitoring is occurring.
Pedicle screws

Hooks have been the mainstay of fixation to the spine in the thoracic region. However there is an increasing argument for the use of pedicle screws. Pedicle screws date back to the early 1900's, but due to breakage and perceived neurological risk have taken a long time to be accepted. They were popularised by Roy Camille in the 1970's and today are accepted as the best form of lumbar and probably thoracolumbar fixation. They are used in the thoracic spine by some surgeons but many others continue to use hooks due to the perceived risks.

One can divide the reasons for using pedicle screws into anatomical, biomechanical and clinical reasons.

Anatomical

The pedicle is the strongest site accessible posteriorly through which a 3 dimensional rigid fixation of the vertebrae can be obtained. This has been utilised by the pedicle hooks, which are similar to sublaminar hooks, having a flat blade. This blade has been modified by notching the tip, so that it is bifid and can be engaged against the pedicle from below. Not only is the screw down the pedicle but it provides firm anchorage into the vertebral body, i.e. having direct contact with the anterior, middle and posterior columns of the spine. These anatomical reasons have biomechanical consequences.

Biomechanical

Krag, Fredericksen and Yuan\textsuperscript{30} summarise the biomechanical literature pertaining to spinal fixation. They show that screw-pedicle-body fixation provides improved security as compared to hook-lamina or wire-lamina fixation. In addition, as the screw has hold into the body as well, i.e. the anterior column, pedicle screw systems convey a better overall positional control than other devices. This provides a secure 3 dimensional positional control of all three columns of the spine, and allows powerful true segmental derotation.

Berkemann et al\textsuperscript{31} performed a biomechanical comparison of the USS pedicle hook, a CD pedicle hook, a prototype pedicle hook and a 5mm USS pedicle screw. This was a laboratory test using cadaver spines. Posterior pull out tests were performed. The
average pull out force of the pedicle screw was 1646.1 N. This occurred at a displacement of 2.5 mm. Most failed by cleaned pull out, with 30% fracturing the pedicle. The average pull out force for the USS hook was 849.0 N. The prototype hook at a pull out force of 1529.9 N, and the CD hook 742.8 N. The hooks failed by pedicle fracture.

Kirkham et al.\textsuperscript{32} performed a biomechanical study of the rigidity of various scoliosis constructs. They found pedicle screw constructs conveyed greater stiffness than other fixation methods, and that minimal additional rotational stiffness was added by transverse connection with cross-links. The use of pedicle screws may therefore obviate the need for cross-links.

\textbf{Clinical.}

Pedicle screws provide immediate rigidity as opposed to hooks, which are easily dislodged. This facilitates easier rod attachment, derotation, compression and distraction. When correctly placed, the spinal canal is not compromised, unlike hooks and wire techniques.

Suk\textsuperscript{33,34} in Korea has been the pioneer of thoracic pedicle screws and has published his experience. He reported on 78 patients, 31 being instrumented with hooks, 23 with pedicle screws inserted in a hook pattern and 24 with segmental pedicle screws. In the patients undergoing segmental pedicle screw fixation, screws were placed in every vertebra on the concavity and alternate levels on the convexity. For the hook group he achieved a 55% correction of the Cobb angle, with a 49% correction maintained at two-year follow-up. The hook pattern screw group a Cobb correction of 66% was achieved, 64% maintained at 2 years. His segmental screw group had a 72% correction, maintaining 71% at two years. There was also a better compensatory curve correction in the segmental screw group. There was a statistically significant improvement ($p=0.000$) in all the sagittal profiles of the hypokyphotic patients, again the segmental screw group having the best restoration of thoracic kyphosis. The segmental screw group had the best rotational correction of 59% to a residual rotation of 8° at the apex. The hook group had an apical rotation correction of 19%. 
Other softer reasons for screws use, is they of lower profile in some systems (e.g. Colorado 2), and there may be a cost advantage, again depending on the system employed.

The main reason pedicle screws in the thoracic scoliotic spine have not been adopted is safety concerns. These safety concerns can be approached as follows:

Is the pedicle big enough?

Vaccaro et al\textsuperscript{15} reported in 1995 on his study of pedicle dimensions. 17 cadaver spines were examined, as were 19 Computer Tomography (CT) scans. These scans were of normal adult spines. The outer pedicle diameters were measured. They were found to range from $4.5 \pm 1.2$ mm at T4 to $7.8 \pm 2.0$ mm at T12. He found that CT scans might under estimate the diameter of the convex pedicles. This study was of course in normal spines, and it may be argued that the scoliotic spine is different.

Liljenquist et al\textsuperscript{16} presented his work at the Scoliosis Society meeting in 1999. He examined 29 consecutive patients treated for Idiopathic right thoracic scoliosis. All these patients were examined by means of Computer Tomography. The average thoracic Cobb angle for this cohort was 60.1°, which is typical of a surgically managed group. The chord length, endosteal pedicle width and the pedicle length were measured. A total of 337 pedicles from T5 to L4 were analysed.

The endosteal cortical diameter varied between 2.5mm at the concavity of T8 and 9.5mm at the concavity of L4. A significantly smaller concave pedicle diameter was found in the apical region of the thoracic curves between T7 and T10 as well as at T12.
They found the antero-medial inclination was highest at the upper thoracic and lower lumbar spine with an average angle of 12° at T5. It was minimal at the lower thoracic spine measuring between 6 and 8° at T11 and T12. The differences between the concavity and convexity were minimal except at the T8 and T12 levels, where the significantly larger angle was found on the convex side.

The chord lengths (figure 4) were shortest at T5, which was 37mm. It increased gradually as one progressed distally.

The pedicle length varied minimally with a range of 20 and 22mm. It was relatively consistent throughout the thoracic spine.

They concluded that the morphometry in scoliotic vertebrae is different to normal with an asymmetrical intravertebral deformity, and therefore pedicle screw instrumentation in the mid-thoracic spine appeared critical due to the small endosteal diameter, especially on the concave side.
O'Brien et al. performed a study to evaluate anatomic constraints of the thoracic vertebra in patients with Adolescent Idiopathic Scoliosis (AIS). 29 patients with operative right thoracic AIS were studied. Preoperative CT was performed. Transverse pedicle width and medial pedicle wall-to-lateral rib wall dimensions, pedicle morphology, and segmental sagittal axial rotation. In addition, plain radiographs were used to measure curve magnitude and the width of the convex apical pedicles on the posteroanterior projections.

Information was collected on 512 pedicles from the CT scans, 256 concave and 256 convex. The mean outside diameter of the concave pedicles from T1-T12 ranged from 5.2 to 8.5mm. The smallest pedicles were identified in the midthoracic region from T5-T8, with the proximal thoracic pedicles (T1-T3) being slightly larger. The largest thoracic pedicles were found from T9-T12. The corresponding dimensions for the convex pedicles ranged from 4.6 to 8.1mm. Pedicle diameter measured on the plain films at the apical level on the convex side showed a range of apparent sizes from 1.5mm to 6.1mm. In all cases but one, scaled CT measurements showed actual pedicle width to be 2-3mm larger than would have been predicted from the plain radiographs.

Review of the pedicle morphology showed that seven concave and seven convex pedicles had a mildly windswept appearance. Stagnara had previously depicted this windswept deformity by an ice-cream seller's bicycle (figure 5). The posterior
elements deform and lose their normal relationship to the anterior column. O'Brien found all of these pedicles to be in the peri-apical region. This altered morphology did not affect the distribution of pedicle size, and would not have interfered with the passage of a pedicle screw.

As regards the segmental rotation, there was no correlation with pedicle size.

They concluded that based on their data, pedicle screw fixation is an anatomically reasonable technique in most patients with AIS. The point is made that the deformity itself (rotation), rather than the local vertebral anatomy, increases the degree of difficulty and potential danger when inserting screws in scoliotic versus non-scoliotic spines.

Suk argued that small pedicle diameters do not preclude screw insertion, as they undergo plastic deformation. This allows screws up to a diameter of 115% of the outer diameter of the pedicle can be used in adolescents. He suggests 4.5mm screws in the upper thoracic spine, 5.5mm for the mid thoracic region and 5.5-6mm for the lower thoracic spine.

Can the screw be accurately inserted?

Vaccaro performed a cadaver study to assess the accuracy of pedicle screw placement and the ability of surgeons to clinically predict their success of screw placement compared with CT scan. 5mm Shanz screws were inserted from T4 to T12 by 4 surgeons familiar with the lumbar pedicle screw technique. After preparation of the pedicle, the surgeons were asked to probe and record if they felt there had been a cortical violation. After insertion of the screw, the specimen underwent CT scanning. After CT, screws were advanced 5mm through the anterior cortex of the vertebral body and the thoracic cavity exposed by median sternotomy. Structures at risk were determined by direct visualisation. Of the 90 screw inserted, 59% were correctly placed within the pedicle and 41% misplaced. Of those misplaced, 43% violated the medial pedicle wall by an average of 4.46mm. The rest were lateral by an average of 2.35mm. Accurate screw placement was more common in the mid-thoracic spine than at the extremes. The ability of the surgeons to predict their success of screw insertion by probing was poor with and overall accuracy of 57%.
When assessing structures at risk, it was noted that correctly placed screws exited the vertebral bodies within 2 cm of the midline. Left-sided screws endangered the oesophagus (T4-9) and the aorta (T5-T12). Appropriately placed right sided screws endangered superior intercostal vessels (T4-5), oesophagus (T4-9), azygous vein (T5-11), inferior vena cava (T11-12) and thoracic duct (T4-12).

When the laterally misplaced screws were advanced they exit the body along the lateral margin. On the left, they endanger the lung, sympathetic chain, segmental vessels and aorta. On the right, the lung, sympathetic chain, segmental vessels and the azygous vein are at risk.

They concluded that pedicle screw fixation of the thoracic spine is technically feasible with a 59% success rate. Some of the pedicle violations were only due to screw exceeding the size of the pedicle. They make the point that it is technically demanding, with risks of surrounding structure damage. They suggest further anatomical studies and suggest preoperative CT and intraoperative plain films.

Liljenquist\textsuperscript{39} reported on 120 thoracic screws in 32 idiopathic scoliosis cases investigated by postoperative CT scans. Overall 25% of screws penetrated the anterior body or pedicle. The penetration rate of convex screws was 23.4% as compared to 28.1% for the concave side. There was an increased incidence of penetration rate with cephalad screws (T4-7) 35.3\% as compared with caudal screws (T8-12) 23.3\%. This was not statistically significant. 8.3\% of screws penetrated the medial pedicle wall with an average of 1.5 mm and a maximum of 3 mm. There were no neurological problems however. 14.2\% of screws were laterally placed by an average of 2.1 mm. 3 screws penetrated the anterior vertebral cortex by an average of 1.7 mm. One of these screws required replacement due to proximity to the aorta.

In the 30 pedicle hooks utilised in their constructs, 16.7\% were noted to have dislocated – 3 medially, and two laterally. No evidence of screw pullout or dislocation was noted.

Suk\textsuperscript{33} in his series of 78 patients had a 3\% misplacement rate (13 screws). 6 were superiorly placed, 5 laterally and two inferiorly.
**Are they safe?**

From recent reports they seem to be safe. Faraj and Webb\textsuperscript{40} reported on 648 pedicle screws of which 140 were thoracic. They had neurological complication rate of 1.09%.

Liljenquist\textsuperscript{39} had no neurological complications in his 32 cases despite a 25% cortical violation rate.

Suk\textsuperscript{33}, in his study comparing hooks and screws discussed above, had no neurological complications in 47 patients with pedicle screw only fixation.
Studies

Two separate studies were performed to assess the clinical and radiological aspects of posterior instrumentation in Scoliosis surgery.

The first study is a prospective randomised trial comparing two instrumentation systems, viz. Colorado 2 and the Universal Spinal System which have a different type of hook system.

The second study was prompted by the recent interest in the use of pedicle screws in the thoracic region despite concerns regarding neurological injury. Here a prospective study was performed on a group of idiopathic scoliosis patients.

The methods and results of each will be discussed separately followed by a combined discussion.
Study 1.

Aim:
The aim of this study was to compare two popular instrumentation systems, viz. the Universal Spinal Systems (USS) and Colorado 2. These are both modular systems made of titanium, allowing multiple fixation options. They have different hook designs, as well as the Colorado having a more flexible rod.

Materials and Method:
Patients with scoliosis requiring surgery were seen at the pre-admission clinic, as is routine for all spinal patients at the Middlesex Hospital. At this consultation, they were re-examined clinically and radiographically.

The surgical planning was done, i.e. whether an anterior release or costoplasty was necessary in addition to the posterior instrumented fusion. To decide whether an anterior release was necessary, the patients skeletal maturity (Risser grade, and secondary sexual characteristics) were taken into account as well as the flexibility of the curve. The flexibility was determined clinically by examination while bending laterally, and radiologically by supine bending films and a pull film. Should the spine be just inflexible, i.e. minimal change on the bending/pull views an anterior release was planned.

The rib prominence was assessed clinically with the aid of a Bunnel Scoliometer. If there was a clinically significant rib prominence a costoplasty was planned. It was considered significant if there was patient unhappiness with the cosmesis of the prominence and a Bunnel angle of greater than 15 degrees was present.

Once the surgical planning was finalised, the patient was randomised into either the Colorado or USS arm. The process of randomisation used was a bag containing 15 cards labelled USS, and 15 labelled Colorado. For each patient the Orthopaedic secretary would draw a card and book the required instrumentation. Twenty-five patients with scoliosis were randomised to this study. There were 12 in the USS arm and 13 in the Colorado arm.

Patient demographics.
Aetiology.

The distribution of cases is illustrated in the above figure 6. Most of the patients had Adolescent idiopathic scoliosis, with 10 in each group. There were two neuromuscular scoliosis in the Colorado group. One patient had had polio as a child and the other was initially thought to be AIS, but was noted to have a syrinx on her MRI. There was one neuromuscular case in the USS group, this being a case of transverse myelitis. There was one syndromic case (Trisomy 6) in the Colorado group and one neurofibromatosis in the USS group. The neurofibromatosis patient had had a previous thoracotomy to remove her neurofibroma and gone on to develop a scoliosis.

Revision surgery.

One of the Colorado cases was a revision with previous scoliosis correction surgery in 1994 becoming infected and requiring subsequent removal of the instrumentation. Once her infection resolved she was re-operated upon and thus randomised to this study.

One of the USS cases had had a previous non-instrumented T4-T6 fusion.

Sex.

There were three males and nine females in the USS group.

There was one male and twelve females in the Colorado group.
The age at surgery.

Figure 7: Age distribution for Colorado group on the left and USS on the right.

Ages were comparable for the two groups (figure 7). The Colorado group had an average of 21.99 years (12.68-48.72±11.17). The USS group had an average of 18.37 years (13.81-33.58±5.41). There was no statistically significant difference, however the Colorado group did have the two oldest patients.

Surgery.

Patients were admitted one to two days before the date of surgery. They were examined by the medical and physiotherapy staff.

After induction of anaesthetic, control of airway achieved and insertion of appropriate lines for venous access and monitoring, they were positioned.

For the anterior release, they were positioned in the lateral decubitus position, with the side of the structural curve upward facing. A thoracotomy was performed, removing the appropriate rib, which was kept for the posterior procedure (frozen). The lung was retracted and the posterior pleura opened longitudinally to expose the thoracic spine. The segmental vessels were left intact, and a plane developed between the pleura and the vertebral bodies and discs. A malleable retractor was placed anterior to the respective disc, deep to the pleura, in a way to protect the vascular structures during the discectomy. A number 15 blade was used to incise the anterior longitudinal ligament and the annulus, extending from the rib head around as far
anteriorly as possible. The disc space was cleared with a Zielke nibbler and pituitary rongeurs. The cartilaginous endplates were removed by means of a Cobb. The space was cleared back to the posterior annulus. This was done at multiple levels. The retro-pleura was repaired to achieve a water-tight closure and thus haemostasis. The chest was closed in layers and an intercostal chest drain inserted.

Overall 7 patients had a transthoracic anterior release, 5 in the Colorado group and 2 in the USS group. The period between the anterior release and posterior fusion was 1 week in 4 cases, 2 weeks in 2 cases and 3 weeks in 1.

An average of 4.43 (3-6±0.976) disc levels were released. The average surgical duration was 107.5 (60-150±33.42) minutes.

The blood loss was an average of 325 (250-400±61.237) ml.

For the definitive posterior corrective surgery, the patient was positioned prone on an appropriately sized Montreal mattress. The abdomen was confirmed to be free and pressure points on the limbs were well padded. A trained technician performed Spinal Cord Monitoring using Spinal Somatosensory Evoked Potentials. Electrodes were placed over the popliteal fossae to stimulate the tibial nerves. The potentials were recorded from an epidural electrode placed once the spine was exposed.

A midline incision was made. Cutting diathermy was used to expose the spine, cutting through the apophyses of the spinous processes. A sub-periosteal dissection was performed to strip the para-spinal muscles off, and expose the lamina and transverse processes. The levels were identified, using image intensification if there was doubt. At the cephalad end, a midline flavotomy was performed and the epidural electrode placed. Normal SSEP traces were confirmed.

Distally, the pedicle screws were placed, usually in a configuration of four. Further fixation was achieved working in a distal to proximal direction, selecting levels and types of fixation on their merits.

When using the USS, hook-screws were the only from of fixation used in the thoracic spine. The facet joint was opened with a hook starter, and the hook driven home, aiming for the pedicle in the mid-facet area of the joint above. Once well located, the jig and 2mm drill were used to drill the pedicle and the interlocking screw placed. For the Colorado, screws and hooks were used in the thoracic spine. The placement for
the hooks was similar to the USS, with firm placement. However, they are interlocked with a staple. This required using a jig over the hook connection, to hammer down and create two of the four holes for the staple pins. Then the staple was passed over the hook connector, and a further tool was struck to "click" the staple in place. These hooks are shown in figure 8.

For the thoracic pedicle screws, the intersection of the mid-transverse process and mid-facetal line was used as illustrated in figure 7. A starter awl was used to broach the cortex, and a curette used to probe down through the pedicle. The direction was confirmed with the use of lateral image intensification. Lateral imaging was convenient as the C-arm was draped sterile and left in the over the top position, simply moving caudal to cephalad to demonstrate the levels and site of pedicles. Antero-posterior imaging was felt unnecessary as it would involve de-sterilising the C-arm, and the medial-lateral aspects of the pedicle could be probed to confirm placement. The walls of the pedicle were felt with the curette and a ball-tipped feeler. Ideally, cancellous bone was felt on all four sides as well as anteriorly (anterior vertebral body wall). Rotation of the spine made this difficult in terms of determining the direction of the pedicle. Once satisfied the feeler was in the pedicle, a screw was inserted.
Once the fixation points were completed, facetectomies were performed with a Capener gouge.

An appropriate sized rod was introduced into the concavity and then the convexity. The concave rod was pre-bent with the desired sagittal profile. The convex rod was under bent to facilitate the anterior force to reduce the rib hump.

The rods were connected to the fixation points. The USS provides powerful instrumentation to facilitate this and uses a technique of pulling the spine up to the rod as opposed to the Colorado, in which the rod was placed in a rotated position, attached and then “derotated” to convert the scoliotic deformity into kyphus. The rod was rotated which does not necessarily mean the spine was. It has been shown that this “derotation” action in fact causes translation of the spine\textsuperscript{29}.

Once the rods were in position some intersegmental distraction/compression was utilised to “fine tune” the correction. Cross-bridges were applied. If indicated the costoplasty was performed at this point.

The spinous processes were removed, and decortication of the lamina done. The locally harvested bone graft plus the rib from the first stage (if done) was prepared into small chips and placed over the decorticated area.

Closure was done in layers, without drainage. The patients were nursed supine for 6 hours to apply pressure on the wound and reduce bleeding, with hourly neurological observations. They were mobilised as soon as possible, usually without a brace.
The duration was similar in the two groups. The average Colorado 2 surgical duration was 203.9 (150-270±38.9), and the USS was 229.6 (150-330±49.3) minutes.

The blood loss for the Colorado group was 1823.1 (850-3800±851.37) and the USS was 2600 (500-7500±2142.4). The USS group was skewed due to an excessive bleed in one patient. She bled 7500ml. No reason was identified. If this extreme is excluded then the average is more comparable to the Colorado 2 group. It reduces to 2110 (500-4000±1471.5).

Costoplasty was performed in 11 cases, 5 in the Colorado group and 6 in the USS.

Patients were braced at the senior surgeons (Mr MA Edgar) discretion. A front and back shell TLSO was used. 2 Colorado and 1 USS case were braced.

They were X-rayed before discharge. They were seen in outpatients at 6 weeks, 3 months, 6 months, one year and two years before discharge. 21 of the 25 patients had a year or more follow-up at the time of this review.

A prospective proforma was completed which detailed the surgical and instrument details as well as radiological and clinical follow up details.

**Results.**

**Cobb angles**

The Cobb angles of the major curves were measured pre-operatively and at the follow-up clinics. This was done on a standing AP whole spine film.

<table>
<thead>
<tr>
<th></th>
<th>Overall</th>
<th>Col 2</th>
<th>USS</th>
</tr>
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<tbody>
<tr>
<td>Pre-op</td>
<td>62.3</td>
<td>58.5</td>
<td>66.2</td>
</tr>
<tr>
<td></td>
<td>(43-105±16.7)</td>
<td>(43-85±13.0)</td>
<td>(44-105±19.2)</td>
</tr>
<tr>
<td>Last f/u</td>
<td>26.0</td>
<td>26.9</td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td>(3-65±13.4)</td>
<td>(16-41±7.2)</td>
<td>(3-65±17.9)</td>
</tr>
<tr>
<td>Correction</td>
<td>59%</td>
<td>53%</td>
<td>65%</td>
</tr>
<tr>
<td></td>
<td>(15-93±17.0)</td>
<td>(15-68±14.8)</td>
<td>(38-93±17.6)</td>
</tr>
</tbody>
</table>

Overall the pre-operative Cobb angle was corrected from 62.3° (43-105±16.7) to 26.0° (3-65±13.4). This is an average correction of 59% (15-93±17).
The USS group had a better average correction of 65% (38-93±17.6) when compared to the Colorado group's 53% (15-68±14.8). However, the residual deformity was similar in both groups with USS 25.2° (3-65±17.9) and Colorado 26.9° (16-41±7.2). The better percentage correction is due to a larger pre-operative average Cobb angle in the USS group. An example of a case using the USS system is illustrated in figure 8.

The Colorado group had a few older patients and a revision case that may explain the lower correction achieved. The difference in correction between the instrumentation groups is not statistically significant with a p value of 0.09.

There were no significant medical problems in any of the patients.

Instrument complications.

Subjectively, the USS hook screw was found to be easy to place. The system provided powerful user-friendly instruments that allowed the translation corrective manoeuvre to be performed.

We had some difficulty with the assembly of the Colorado stapled hook. One is reluctant to hammer down onto the spine with the staple jig to prepare the staple holes, especially as laminas cortex resist the tool. To apply the staple there was also some difficulty, especially in clicking the clip to fasten the staple to the screw. This may explain some of the problems discussed later.

As far as complications were concerned there was one in the USS group. Intra-operatively a T3 hook screw cut out during the corrective manoeuvre. This was removed and replaced at the T5 level without further problems. This patient had had a previous uninstrumented T4 to T6 fusion. Possibly this inflexibility and an overzealous reduction force was responsible for this hook cut out.

There was no loss of correction in the follow up period of the USS group. None of the USS cases required subsequent surgery.

The Colorado group also had an intra-operative T3 lamina fracture. This was replaced and increased kyphus bend put on the rod. This patient went on to develop junctional kyphosis and required further surgery at another institution. However, this
complication is probably due to inadequate length of fusion superiorly rather than a failure of the instrumentation.

There was loss of hook position in four cases. It was thought that all hooks were well placed during surgery, however on early post-operative X-rays (2 to 3 days) misplacement/dislodgement was evident. We feel that this occurred either during the correction manoeuvre or early post-operatively on mobilisation. The derotation technique was utilised to correct the scoliosis deformity in the Colorado group. Here pre-bent the rod is laid into the concavity of the curve and attached to the fixation points. The rod is then rotated into the sagittal plain so that the coronal deformity is corrected and kyphosis is introduced to the thoracic spine. This derotation is transmitted via the hooks/screws to the spine. This may have been the cause of the hook dislodgement, as the hooks are not stable points unless they are under load in the cephalad direction. Figure 9 illustrates the Colorado hook dislodgement.

Pedicle screws are better for this very reason. Due to this observation and the difficulty inserting the Colorado hooks, the senior surgeon elected to start to use pedicle screws in the thoracic spine in addition to the hooks, but only in the Colorado group as subjectively the USS hook screw was not showing the same problems.

This however led to its own problems. Pedicle screws are difficult in the thoracic spine and with the early part of the learning curve, there were misplacements of 5 screws in four patients. 4 of these screws were misplaced laterally in the costo-transverse joint, and one medially in the spinal canal.

Three of these misplaced screws went on to pull out. Two of the patients required rod trimming and the third has prominent metalwork, but has elected to leave it as is as she is asymptomatic.

There has been no loss of correction in the Colorado group. This is between the post-operative X-ray and the last follow-up. However, there does appear to have been early loss of correction between hook insertion, correction and early post-operative correction, which would explain the lower Colorado group average correction.

Due to the problems related to the cephalad fixation with the Colorado hooks and recent reports of improved deformity correction with pedicle screws\cite{33,34,39}, the second
study was initiated to assess the use of purely pedicle screw fixation in the correction of Idiopathic Scoliosis.

Figure 8: Good correction achieved with a simple USS construct, improving the Cobb angle from 102° to 50° in a 19 year old male with an inflexible curve. Further correction may have been possible with apical fixation, but there is always a balance between radiological improvement and risk. This patient was extremely happy with his result.
Figure 9: These two cases demonstrate the Colorado hooks which had dislodged. In theatre they were thought to have been correctly placed. However on the immediate post-operative views show how the concavity superior hooks have rotated round the pedicle, and the convex pedicles have dislodged superiorly from the pedicle hook. The left case shows the superior hook lateral to the pedicle.
Study 2.

Aim.

The aim was to assess whether pedicle screw only fixation was possible in Idiopathic Scoliosis with reference to the abnormal anatomy, whether the correction achieved was any better than existing techniques, and whether the complication profile was any different.

Materials and Methods.

17 idiopathic scoliosis patients were operated on using the Colorado 2 system during a period from 1998 to 2000. Pedicle screws were the only method of fixation. The same pre-admission procedure was used as in Study 1.

There were 16 females and 1 male. The average age at surgery was 30.3 years (11.9 to 56.3 ± 16.4). 7 patients were adolescents, the rest having adolescent onset curves, but presented in adulthood.

The King classification\(^49\) of the curves was as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of cases</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
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Transthoracic anterior releases were performed in 5 patients, 4 as a separate stage and 1 at the same sitting as the posterior stage. Between 4 and 6 discectomies were performed. Costoplasties were performed in 4 cases. The techniques employed were those as described in study 1.

Spinal cord monitoring was employed using spinal somatosensory evoked potentials recording via an epidural electrode placed at the time of surgical exposure.
A standard posterior approach was used. Pedicle screws were inserted using the entry point as suggested by Suk\textsuperscript{33,34}. This is the intersection of the mid-facetal line and the middle of the transverse process. A starter awl was used to broach the cortex, and a probe used to find the pedicle. The four walls of the pedicle were probed, and if uncertain the position was checked by lateral fluoroscopy.

Standard facetectomies and decortication was done. The rods were applied and corrective manoeuvres performed. Local bone graft was applied, combining the osteotomised spinous process, and rib if an anterior procedure or costoplasty had been done.

Patients were nursed supine for 6 hours, then turned 2 hourly. They were mobilised the following day. 3 were braced on the senior surgeon's discretion.

The patients were X-rayed once able to stand. Once discharged they were reviewed at 6 weeks, 3 months, 6 months and one year. At these appointments they were re-X-rayed. The Cobb angle was measured using the same levels as the pre-operative measurement and the percentage correction calculated.

Anterior Posterior and lateral projections were used to assess the pedicle screw placement. This imaging technique has been validated by Faraj and Webb\textsuperscript{40}. Doubtful placements were investigated by CT scan.

**Results.**

A total of 170 pedicle screws were placed, of which 119 were thoracic and the rest lumbar. The breakdown was as follows:

<table>
<thead>
<tr>
<th>Level</th>
<th>No. of Screws</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2-4</td>
<td>16</td>
</tr>
<tr>
<td>T5-8</td>
<td>46</td>
</tr>
<tr>
<td>T9-T12</td>
<td>57</td>
</tr>
</tbody>
</table>
Cobb angle correction.

As regards deformity correction, the average pre-operative Cobb angle was improved from 66.5° (40-95±18.5) to 28.1° (12-56±12.4). This is an average post-operative correction of 59.6%. At 6 months the average Cobb angle was 30.1° (12-48±9.8).

There were problems of misplacement and pullout. Figure 11 demonstrates the correction achieved in a King 2 curve.

Screw misplacement:

Four screws were misplaced in three patients. In one case, the two screws were misplaced. In another case a pedicle was split intra-operatively resulting in misplacement. In a further case a screw was misplaced resulting in a pullout. All of these screws were imaged by axial CT. This demonstrated that 3 were placed lateral to the pedicle and medial rib head, i.e. in the costotransverse joint. On probing intra-operatively the rib head would be felt laterally and would give the false impression that the probe has bone on all sides. With experience, one could identify the rib head by its rounded smooth feel, as opposed to the rough cancellous bone. Figures 12 and 13 illustrate lateral placement.

One was placed medially violating the spinal canal (figure 15).

Screw pullout:

Three screws in two patients went on to back out. These were the most superior screws on the convex side of the curve. One of these screws had been misplaced, resulting in poor fixation. The pullouts were all evident on the immediate post-operative X-ray, and probably gave way during the correction process, particularly the rotation of the rod (figure 14).

Loss of correction.

In the one case, the pullout resulted in a 12° loss of correction in the first 6 months. The patient still maintained a 30% correction, with a residual Cobb angle of 39°.

The case with the split pedicle had an 11° loss of correction between 3 and 6 months post operatively. She had a residual Cobb angle of 29°.

There was no loss of correction in the remaining 15 cases.
Revision procedures.

One case was revised due to pullout and a prominent rod. The superior part of the rod was trimmed.

Neurological complications.

There were no neurological complications.

Wound infection.

Two cases developed wound infection. Both were managed with oral antibiotics.

Figure 11: This case demonstrates the power of segmental fixation, especially pedicle screw fixation. This King 2 curve has been treated by addressing the thoracic curve leaving the lumbar curve mobile.
Figure 12: These two cases demonstrate pedicle screws which have been misplaced laterally.
Figure 13: This sequence of CT scans confirms a screw to be laterally misplaced in the costo-transverse joint and into the rib head. The pedicle does appear small and sclerotic.
Figure 14: Intraoperative fluoroscopy confirmed placement of the superior screws on the lateral. However, the first postoperative lateral X-ray shows the superior two screws to have pulled out. Subsequent CT shows the superior screw to be laterally misplaced, and the cause of the pullout. The right misplaced screw is on the left hand side of the CT picture.
Figure 15: A further case where the pedicle screw had been placed medially. This was the only screw to be identified to have been misplaced medially. The CT confirms the screw breaching the pedicle and traversing the lateral part of the canal. There were no neurological sequelae in this patient and the screw has not been removed.
**Discussion**

The approach and practice of corrective surgery for scoliosis has evolved over time, from humble beginnings of uninstrumented in-situ fusion to expectations of 65% Cobb angle correction using multiple fixation points and dual rod systems. Our understanding has developed from a limited coronal plane correction, to appreciation that scoliosis is a three dimensional deformity. With current segmental systems we are able to exert corrective forces across all three columns of the spine, providing correction in the coronal, sagittal and axial planes. The aim is to restore the normal anatomical profile of the spine and thereby optimise the biomechanics of the remaining mobile segments, in an effort to prevent early degenerative changes and pain. By approaching normal anatomical profile the outward bodily shape is also improved, allowing these often young patients the confidence to engage in normal life.

In the first study comparing the two modular posterior fixation systems, viz. Colorado 2 and USS, the groups were comparable as regards demographics. There was no significant difference in the average ages of the group, although there were older patients in the Colorado group. There was a high proportion of females in both groups, which is in keeping with the nature of Scoliosis. There were more anterior releases performed in the Colorado group, possibly indicating more inflexible curves. However, the release should render them flexible, in terms of ease and degree of correction.

Intra-operatively, the USS was found to be a more “user-friendly” system. The instrumentation available made the required procedures easier. This was particularly evident when placing a pedicle hook-screw, and when attaching the fixation points to the rod. The procedure of securing the hook-screw using the drill guide was simple and effective, as compared to the Colorado securing procedure that was subjectively found to be difficult and “fiddly”. The process of hammering the staple down into the lamina was often ineffective, with the spine bouncing away rather than allowing the staple points to penetrate the cortex. This difficulty resulted in avoidance of using the staple with resultant hook dislodgement during the correction manoeuvre. This later
led to the use of pedicle screws in preference to the stapled hook. The insertion of the pedicle screw is more time consuming and requires repetitive checking with image intensification, as compared to the pedicle hook which is a quick and simple procedure.

The USS system provides useful tools to attach the fixation points to the rod. The Complexo device allows controlled pulling of the spine to the rod by a distraction manoeuvre pulling the screw posteriorly to the rod, followed by lateral translation by compression of the tool. This was found to be an extremely useful device. The Colorado system relies on simply pulling the clamp to the rod with a clamp holder, or using the derotation method. This proved difficult at times, especially with the long headed Colorado screws, requiring the clamp to be lifted “over the top”. These screw head extensions are only broken off during final tightening.

As far as coronal deformity correction was concerned, there was no statistical difference. However there was a trend to better correction using the USS system. The maximum correction was performed using the USS. One needs to be careful when looking at percentage correction though, as often the goal is a stable balanced spine rather than a radiologically straight spine. One may elect to under correct a thoracic curve to maintain balance with a residual lumbar curve. Also, the residual curves were very similar (around 25°), with the superior correction in the USS group being due to a larger pre-operative angle.

Of importance is that once corrected there was no deterioration of results in either group. This is in contrast to earlier instrumentation, where loss of correction was as often reported. This is in spite of the fact that bracing was seldom used, only 3 out of 25 cases. This demonstrates the powerful fixation these systems allow.

We were unable to reliably record the sagittal angles, as often the cephalad thoracic endplates were not clear on the X-rays. For those recorded there was no difference between the groups. The axial correction was not done, as the only reliable method is CT, which we did not perform as a routine. It is difficult to record the Nash-Moe or
Pedriolle from the X-rays once dual rods have been applied. These methods have also been reported to be inaccurate.

The major difference between the systems was problems with the cephalad fixation in the thoracic spine. Both groups had an intra-operative lamina fracture requiring replacement of the hook at another level. This was related to surgical technique with excessive force rather than an instrument problem.

There were no further USS instrumentation problems. On follow-up X-rays all hooks appeared well placed and remained so over sequential X-rays. No patients in the USS group required further surgery.

In contrast the Colorado group had multiple problems with the cephalad fixation. Three patients demonstrated hook misplacement on the post-operative film. Intra-operatively it was felt that the hooks had been well placed, and this is thought to represent dislodgement during the correction manoeuvre. Despite the staples being used on the convex hooks, they moved off the pedicles.

Due to difficulty inserting the hooks and dislodgement, the senior surgeon started to use pedicle screws at the superior end of the construct. Being early in the learning curve, there were problems with these. A further 4 cases demonstrated misplaced screws. As a result of these misplaced screws, three backed out. Two were symptomatic and required superior rod resection. One remains prominent, but asymptomatic and has been left alone.

The patient with the lamina fracture developed junctional kyphosis with prominent metalwork and required superior trimming and hook removal.

The problem with the hook fixation and reports of superior correction with thoracic pedicle screws resulted in the second study where pedicle screw only constructs were utilised.

Our pedicle screw only group had an average Cobb angle correction of 59.6%. This compares favourably with Suk’s super hook group with a maintained correction of 49% (despite an initial correction of 55%). His segmental screw group had a better correction of 72%. Our results were similar to his hook pattern screw group (64%) as
would be expected. In terms of coronal correction, Harrington rods can achieve 50%\textsuperscript{15,16,18} but use distraction as opposed to translation with the inherent risks of neurological injury. The current modular systems are more expensive, and one may argue that the Harrington-Luque technique offers segmental correction. However, there is a definite neurological risk with the passage (and removal) of sub-laminar wires\textsuperscript{11,12,18}, which is in excess of that reported with current modular systems\textsuperscript{33,39,40}.

Once familiar with the modular systems, there is no real difference in time with Harrington-Luque versus a hook-screw system, as the passage of sub-laminar wires is also time-consuming. The literature indicates that true three dimensional correction can be achieved safely with the current systems\textsuperscript{22,23,33}, with better correction than with the older techniques.

The question of cost is always difficult, as does the increase in correction really justify the cost? The hook pattern screw constructs yield good results with a reasonable cost, and is a good compromise between Harrington instrumentation and every level screw fixation. The move to titanium is necessary to allow subsequent MRI investigation if required, and the versatility of modular systems justifies the increased expense. The increased cost of screws at every level is probably not justified in our practice.

The anatomy of the pedicles has been discussed before. The screws were placed using lateral image intensification and probing to confirm surrounding bone. Despite this there were misplacements.

Four screws in three patients were identified as misplaced on the X-rays and confirmed by means of CT scanning. Three were misplaced laterally. This is thought to be due to the false impression of surrounding bone when probing into the costo-transverse joint. The rib head laterally misrepresents the lateral cortex. Once this was realised, it was possible to identify the rib head in subsequent cases by its rather smooth feel as compared to the rough cancellous bone of the pedicle. Also, if in the pedicle and vertebral body, one feels a very definite end point anteriorly, as opposed to when straying into the costo-transverse joint there is no definite endpoint.

One of the four misplaced screws was misplaced medially across the side of the canal. There was no change in her neurology.
Three screws in two patients went on to back out. These were the most superior screws on the convex side of the curve. One of these screws had been misplaced, thereby never offering a good fix. The pullouts were all evident on the immediate post-operative X-ray, and probably gave way during the correction process, particularly the rotation of rod.

Our misplacement rate of 3.4% (4 out of 117 thoracic screws) is similar to Suk\textsuperscript{33} (3%). As with Suk, our most frequent misplacement was lateral. Liljenqvist\textsuperscript{39} had a somewhat higher misplacement rate of 22.5%. This may due to the inclusion of minor cortical violation, i.e. when the screw thread breaches the cortex, which does not have a significant risk of injury. Despite these misplacements, neither Suk nor Liljenqvist experienced neurological injury.

In the pedicle screw only cohort, 2 out of 17 patients had some loss of correction. One was related to pullout, and the other was a case with an intra-operative split pedicle with a laterally misplaced screw. The loss of correction was rather small leaving the respective cases with acceptable correction. Neither of these two cases had been braced.

The case with the pullout and loss of correction required subsequent trimming of the superior rod. One of the other screw pullout patients also required subsequent rod trimming.

There is no doubt a place for the pedicle screw in the thoracic spine. The challenge would be to develop techniques to improve the safety and reliability of placement. There is a learning curve and with practice one has less difficulty placing the screw.

Cincotti et al\textsuperscript{143} reports on an anatomical and cadaver study, where they found the pedicle to be in line with a more lateral entry point. They suggest that instead of the mid-facetal line as used in our studies, one enter at the junction on the middle and lateral thirds of the facet, again at the level of the superior transverse process. In their cadaver study they had lower cortical violations with the lateral entry site.
Xu suggests the use of partial laminectomy to find the medial and superior walls of the pedicle. In a cadaver study, they placed screws into T1 to T10, using the standard technique on the right and the partial laminectomy on the left. They found a significant difference. With the standard technique, there were 54% violations compared to 15.9% with the laminectomy.

An interesting area of development is the use of Computer assisted guidance systems. These are based on either fluoroscopy or pre-surgical CT data acquisition. The instruments are then defined by position in space and correlated with the imaging on monitors. This allows the surgeon to see his probe or screw position in terms of axial, sagittal and coronal images. At present there is still up to 1mm error built into the systems. When dealing with pedicles of 5mm, this is probably not good enough. The systems are expensive, but the enthusiasts maintain they are worthwhile. One must weigh this up with the fact that despite minor cortical violation, the incidence of neurological injury is low. For years, surgeons have been entering the canal with wires and hooks, so the presence of minor violation by a screw is probably of interest only. However, with severe rotation, it can be extremely difficult to judge the direction of the pedicle from posterior. There main use may be in revision surgery where the posterior landmarks are distorted, making pedicle entry site identification extremely difficult.
Conclusion.

With modern modular fixation systems, good correction can be achieved with low complication risk. There is no statistical difference between the Colorado 2 and USS systems as regards correction, but there seems to be a weakness with the Colorado pedicle hook design. Attempts to bypass this by using screws have led to misplacement, pullout and subsequent rod trimming in a few patients. However this may be explained by the early use of this technique, which will improve with familiarity.

The second study shows that despite concern regarding pedicle size, pedicle screw constructs are possible. They yield good correction of the deformity, with minimal misplacement and resultant complications.
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