State of the Art in Medicine

WILLIAM M. THOMPSON, MD, *Editor*

Spinal Instrumentation

Evolution and State of the Art

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THE NUMBER AND TYPES of implants available for spine surgery have greatly increased in recent years. Many are carefully designed with careful consideration of the problems being addressed; others are merely an attempt to capture a market. This article reviews the development of spinal instrumentation to the current state of the art, to clarify the aspects of design which must be considered. Designing an implant to address one problem can result in another. All currently understood aspects of spinal disorders must be reviewed before effective instrumentation can be applied or evaluated. This review is preceded by an overview of spinal disorders to ensure that critical clinical and biomechanical problems are understood.

Spinal disorders include a wide range of pathology. Most problems are treated initially with conservative modalities. Surgery is recommended if these modalities fail. Treatment of scoliosis was the first widespread application of spine instrumentation. Spine fractures as well as spines destabilized by tumor or infection also may necessitate the use of implants. The last indication for the application of spinal implants, which will be discussed, is degenerative conditions of the spine, most commonly in the lumbar spine.

Scoliosis

There are types of scoliosis: congenital, neuromuscular, and idiopathic. The coronal curve is only part of the problem. The visible deformity (the rib hump) actually is caused by the rotational component. Curvatures measuring more than 80° to 90° can result in significant alterations of the thoracic cage, resulting in cardiopulmonary compromise.[1] Skeletally immature patients are at greatest risk for progression.

Conservative treatment, such as bracing or casting, aim at preventing or slowing progression and require curve flexibility and growth potential to be effective. Because of this, adult and congenital scoliosis are not usually responsive to bracing. If a curve is at high risk for progressing and is of significant magnitude, surgical fusion may be indicated. This can be done in situ, that is, without attempt at correction, or with correction, either by postoperative casting,[2,3] traction,[4] or, as is more commonly done today, internal correction with rods, hooks, or wires (see Posterior Thoracolumbar Instrumentation section).

Congenital Scoliosis

Patients with congenital scoliosis often have other congenital abnormalities. Those of the genitourinary system are the most common, followed by cardiac abnormalities and

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other spinal column abnormalities, including intracanal pathology such as syringomyelia, tethered cord, diastematomyelia, or diplomyelia. These patients should be evaluated for other system abnormalities, and a magnetic resonance image or myelogram/computed tomographic scan of the spine needs to be performed if surgery is contemplated. If a syrinx is not drained or a tethered cord is not released, devastating neurologic complications can result.

Neuromuscular Scoliosis

Neuromuscular scoliosis, such as occurs in cerebral palsy, muscular dystrophy, and spinal muscular atrophy, can present additional problems. These curvatures, collapsing in nature due to muscular weakness or imbalance, often include the sacrum and may result in pelvic obliquity. These patients often have osteoporotic bone, which poses additional challenges to the spine surgeon.

Spinal Trauma

Spinal trauma can result in various fracture patterns, many of which can heal with prolonged bedrest. However, this is often a less-than-ideal option because of the resulting complications, such as atelectasis, pneumonia, deep vein thrombosis, pulmonary embolus, and pressure sores. Much work has been done to define and classify fractures, both mechanistically[5] and morphologically,[6–8] to predict which fractures will be unstable in the acute or chronic state. Holdsworth[7] defined the spine as a two-column model. The anterior elements are comprised of vertebral body, intervertebral disc, and anterior and posterior longitudinal ligaments. The posterior elements include the lamina, facet joints, ligamentum flavum, and interspinous and intertransverse ligaments. He believed that when both columns were disrupted, which could occur either in distraction or compression, the spine was rendered unstable. In 1983, Denis[6] proposed a three-column spine model where the middle column, comprised of the posterior aspect of the vertebral body and disc and posterior longitudinal ligament, was the keystone to spinal stability. If the middle column was disrupted, which usually occurred in conjunction with anterior and/or posterior column disruption, the spine was deemed unstable. Others have refined these definitions and believe that, for burst fractures (the most common fracture type with middle column disruption) if the kyphotic deformity progressed more than 20°, was greater than 40°, or there was greater than 50% loss of vertebral body height, the fracture was believed to be unstable in the acute stage.[9] Patients with incomplete neurologic injury and unstable fractures risk further damage to their neural elements, and stabilization is recommended.[10]

In addition, patients with incomplete neurologic injuries who have evidence of canal compromise may be indicated for surgical decompression, because removal of a compressing bone or disc fragment appears to improve the prognosis for neurologic recovery.[11–14] The specific timing of decompression, immediate, acute, or late, is debatable.

Infections and Tumors

Infections or tumors (primary or metastatic) of the spinal column can compromise spine stability, with the risk of damage to the neural elements or progressive deformity. The surgical problem is similar to that encountered with spine fractures. Surgical decompression, often including fusion with instrumentation, may be necessary to prevent deformity or later canal compromise.

Degenerative Disease

Spine injuries and age are factors that can contribute to degenerative changes in the spine, most commonly in the lumbar spine. These changes can be manifest as disc space narrowing, osteophyte formation, facet joint narrowing, or facet process hypertrophy and can cause varying amounts of back or leg pain. Patients with these symptoms may be candidates for surgery if they are resistant to conservative measures, such as physical therapy and exercises, nonsteroidal anti-inflammatory medications, or epidural or facet injections. Spine fusion may be indicated if a wide decompression, potentially destabilizing the spine, is needed to relieve stenosis, or if it is desired to immobilize one or more motion segments. Instrumentation may be used, depending on various factors, including surgeon preference, previous surgery, and history of smoking. The pseudarthrosis rate without instrumentation varies from 1% to 10% for single-level fusions[15–18] (Ransom NA, et al; American Academy of Orthopaedic Surgeons, February 13, 1990), increases with the number of levels fused, and appears to be improved with appropriate instrumentation.

The Goals of Instrumentation

With the application of spinal instrumentation, the following goals are expected to be reached. Implants should maintain correction after deformity surgery to degrees unobtainable with casting techniques. Unstable spinal segments, resulting from trauma, metabolic bone disease, degeneration, or neoplastic processes, are instrumented to stabilize the bony canal and prevent neurologic damage and deformity. Solid immobilization may enhance bony fusion.[19–21] Early surgical stabilization facilitates rehabilitation,[22–27] thereby avoiding the detrimental effects of recumbency.[28,29] Certain spinal instrumentation may free the high-risk, neurologically impaired patient from external immobilization.

The evolution of spinal instrumentation clearly parallels the recognition and achievement of these goals. Although no single type of instrumentation can universally be applied to every pathologic finding, the myriad devices currently available permits selective use for maximum benefit.

Historic Perspective

In 1891, Hadra[30] was credited with the first application of spinal instrumentation when he used wire to stabilize a cervical fracture dislocation. During the next 4 decades, reports documented the use of screws,[8,31,32] spinous process plates,[33] bone pegs,[34] rods,[35] and springs[36] to correct spinal deformity, treat instability, and enhance spinal fusion rates. Failure was common with these methods and led to low acceptance among spinal surgeons.

By the late 1940s, a growing population of poliomyelitis patients with scoliosis increased the awareness of treatment limitations available to stem progressive, collapsing spinal deformity. During that period, Harrington began to develop his spinal instrumentation system. In 1962, Harrington[37] presented an initial series of spinal deformity patients treated with instrumentation and postoperative cast immobilization. Clinical failures using the Harrington technique provided the impetus for modifications of his original instrumentation.

All instrumentation systems apply stabilizing or corrective forces on spinal segments. The points of fixation—anterior, posterior, or transpedicular—define their fundamental differences.

Posterior Thoracolumbar Instrumentation

The original Harrington instrumentation was a major advancement in the treatment of spinal deformity. Stainless steel hooks and rods were applied to the concavity of the spine in distraction. Distraction hooks were originally placed under the laminae at the caudal and cephalad ends of the instrumentation. Lateralization of the cephalad hooks out of the canal and into the facet joints was an early modification, resulting in a decreased risk of spinal cord compression and improved fixation. In 1973, Harrington published an 11-year follow-up on 578 patients with adolescent idiopathic scoliosis, who were treated with his spinal instrumentation; average frontal curve correction was 54%. A 4% documented pseudarthrosis rate was a significant improvement over results obtained with fusion followed by corrective casting.[31,37] This success was tempered by instrumentation complications in 21%, including 12 hook dislocations, 24 broken rods, and 87 changes in instrumentation position. Other authors had a similar experience,[38] including pseudarthrosis rates of 15% in adult scoliosis.[39]

Posterior distraction forces applied by hooks and rods introduced several problems. Concentrated hook forces on thin lamina produced metal–bone failure by fracture, dislodgement, or bone resorption[40–44] (Edwards CC, et al. Proceedings of the Scoliosis Research Society, 1984). Ratchets at the rod end provided a method for gradual hook distraction, but also generated a stress riser at the ratchet-smooth rod interface where metal fatigue fractures could occur.[45–47] Biomechanically, axial distraction alone, without transverse forces, is more effective for straightening large, long curves. Therefore, the original Harrington distraction instrumentation had limited correction potential for other deformities.[48,49] Several instrument modifications attempted to solve these problems: hooks placed in compression on the convexity of the curves, hook shape changes[3] (Edwards CC, et al. Proceedings of the Scoliosis Research Society, 1984), new rod ratchet and thread designs,[23,47] and the addition of cross linking devices between the distraction and compression rods,[50,51] to name a few.

Harrington distraction-compression instrumentation addressed the frontal curve abnormality, but the physiologic sagittal contour was often negatively influenced, particularly when applied to the lumbar spine. Sagittal contours were not discussed in Harrington's early series of patients with idiopathic scoliosis.[37] Distraction across the lumbar spine tended to reverse the normal lordosis (Flatback syndrome) leading to patient decompensation in flexion and subsequent pain.[52–55] Moe and Denis[55] introduced a modified square-ended Harrington rod with a complimentary hook rod collar (Moe Hook, Zinner, Warsaw, IN) in an attempt to avoid flatback. Coupling the rod and hook made contouring of the lumbar rod possible. In practice, however, a contoured lumbar rod decreased the effective distraction force and added little to the torsional stability of the construct.[41,56] Another modification, the Edwards Rod Sleeve, provided three-point fixation, and also was designed to allow the maintenance of lumbar lordosis and improve torsional stability with distraction instrumentation.[57]

With the Harrington technique, the convex compression rod was originally thought to improve the deformity correction potential when used in combination with a concave distraction rod. However, compression instrumentation applied to a hypokyphotic thoracic curve tended to exacerbate the sagittal deformity.[58] Gaines and Leatherman[59] suggested that the compression rod improved the rib deformity; however, many surgeons abandoned its use because it added little to the stability of the construct and did not appear to improve the frontal correction.[2,50]

Segmental instrumentation

Eduardo Luque of Mexico introduced an instrumentation system in 1973 in response to the limitations of Harrington instrumentation. Poor patient follow-up and the hot, humid climate in Mexico made postoperative casting impractical for Luque's patients.[60] Used with this system are two smooth rods that are affixed to the posterior spine through sublaminar wires at each level and contoured to physiologic sagittal curves. By distributing the corrective forces over multiple levels, the force per level is reduced and the overall potential correction is increased. In contrast to distraction instrumentation, transverse forces applied by reducing the spine to the rod through segmental wire fixation made the system ideal for correcting short, kyphotic curves. Biomechanical studies support the high degree of stability of the Luque construct[20,61,62] (Mann KA, et al. Presented to the Orthopaedic Research Society, January 21, 1987).

Luque reported on a series of 322 patients treated with segmental sublaminar instrumentation and fusion in 1982. Instrumentation failure occurred in 27 of these patients, but the rate declined in a subsequent series after larger three-sixteenth– and one-quarter–inch L-rods were used. Five percent of these patients had pseudarthrosis. The foot of the L-rod is seated through the base of the spinous process which, according to Luque, decreased fatigue and migration of the rods. Although a criticism of the Luque technique was that wiring at each level results in less bony surface available for placement of bone graft, the low pseudarthrosis rate suggests that enhanced stability and rigid immobilization are produced.[60] Luque's results are particularly impressive because they included patients with poliomyelitis, spasticity, paraplegia, and other neuromuscular disorders.

Of major concern with the Luque system is the risk of neural damage associated with the passage of sublaminar wires either at the time of placement or subsequent removal[63–66] (Blackman R, Toton J. Proceedings of the Scoliosis Research Society, 1984). For patients with idiopathic scoliosis, motor cord injury rates are 0% to 3% compared with 0.5% with Harrington instrumentation.[31] Minor sensory changes were noted in up to 22% of patients with Luque instrumentation.[67–70] Zindrick et al[71] have discussed techniques for minimizing the risk of neural canal encroachment during the passage of sublaminar wires.

Most spine surgeons now agree that the primary role of Luque instrumentation is in the treatment of patients with neuromuscular scoliosis, particularly in patients with osteoporosis, muscular dystrophy, or where the spasticity of cerebral palsy, for example, places additional stresses on the bone–metal interface.[62,72] The benefits of segmental fixation in these patients outweigh the associated risk of neurologic injury. Unstable spine injuries in patients with complete spinal cord injuries, where the injury is relatively cephalad, may be another relative indication.

Sublaminar wires also may be selected in adult scoliosis in patients with significant osteoporosis, so that multiple fixation points may disperse the stresses on bone, decreasing the likelihood of instrumentation pullout. The prudence of risking neurologic injury with the passage of multiple sublaminar wires in patients with adolescent idiopathic scoliosis has been questioned.[74]

Hybrid devices attempt to apply the best characteristics of both systems. The so-called "Harri-Luque" technique is an example of one such hybrid system. With the Harri-Luque technique, *standard Harrington distraction rods segmentally* affixed with sublaminar wires are used. A major drawback of the Harri-Luque technique was an increased risk of hook encroachment into the spinal canal because the rods are approximated to the spine.[75] Moreover, the placement of segmental sublaminar wires continued to place neurologic structures at risk.

To gain the benefits of segmental fixation without the associated neurologic risks of sublaminar wiring, Drummond et al[76] and Guadagni et al[77] used spinous process wires. Their construct applied a Harrington distraction rod on the curve concavity and a Luque rod on the curve convexity. The rods were connected segmentally with wires passed through buttons at the base of the spinous process (Wisconsin interspinous segmental instrumentation). Decreased area for bone grafting and increased operative time were the drawbacks of this technique.[69] The developers of the Wisconsin technique believed that their fixation strength was close to that of a Luque construct.[76] In contrast, Wenger et al[78] reported peak pull-out loads of 1,035 and 1,970 N for sublaminar wires placed in the thoracic and lumbar spine, respectively compared with loads of 285 to 420 N for spinous process wires. Although spinous process wires have less pull-out strength than sublaminar wires, the multiple sites of fixation most likely account for the good results achieved with the Wisconsin technique.

With a spinal deformity such as idiopathic scoliosis, the original Harrington instrumentation succeeded in providing an "internal splint" until the surgically applied fusion mass matured. However, the construct is weak in torsion,[51] and a cast or brace was needed to protect the fusion. When applied to an unstable spine, such as after trauma or tumor excision, the limitations of Harrington instrumentation became apparent. McAfee and Bohlman[26] studied 40 patients with fractures of the thoracolumbar spine treated with Harrington instrumentation. Hook dislodgement, rod breakage, and failure to accomplish or maintain reduction were some of the complications listed. Failure to recognize unstable fracture patterns (ie, flexion–rotation injuries) is cited as one of the factors for instrumentation failure. Competence of the posterior longitudinal ligament is required to act as a check rein when applying distraction to unstable spinal fractures. Failure to recognize ligamentous disruption was a cause of overdistraction in McAfee and Bohlman's series. Use of supplemental fixation points, via sublaminar or, more safely, spinous process wires or with Edwards sleeves, appears to afford greater stability to the construct.

A disadvantage of Harrington instrumentation is the number of instrumented vertebrae required to immobilize an unstable spinal motion segment. Gurr et al[20] studied an unstable calf-spine model to analyze the effect of posterior instrumentation on post-laminectomy specimens. They concluded that as many as five vertebral levels may need to be instrumented to confer stability to the operated segment using Harrington instrumentation. Emphasizing the importance of limiting the number of segments instrumented, Cochran et al[79] established that preservation of lumbar motion segments is critical in avoiding low back pain below spinal fusions. The compromise technique of "rod long and fuse short'' has been largely abandoned with the recognition that spinal segments immobilized under compression and distraction instrumentation will show histologic evidence of facet degeneration.[80,81]

Cotrel-Dubousset Instrumentation

In the treatment of idiopathic scoliosis, segmental fixation with wire improved the correction of the frontal plane deformity while maintaining physiologic sagittal contours. Nevertheless, idiopathic scoliosis is considered a deformity in three dimensions (axial rotation not significantly being affected by these techniques).[82] With the introduction of Cotrel-Dubousset instrumentation (CDI) into the United States in 1984, the developers claimed that through strict adherence to their principles, a derotation force could be obtained.[83] Theoretically, if spinal rotation is linked to the production of the rib hump (Closkey RF, et al. Presented at the Annual Meeting of the Scoliosis Research Society, Baltimore, MD, 1988), derotation could potentially improve the part of the deformity (the rib hump) that many patients agree is cosmetically unacceptable.

CDI uses multiple laminar and pedicular hooks placed at selected levels along the concave and convex rods. Pedicle screws (see ''Pedicle Screw Instrumentation'' section below for further description) also can be attached to the rods. In general, the hooks on the concave side of the curvature are arranged for distraction while the convex hooks provide compression. Viewed in three dimensions, the concavity of the curve is hypokyphotic and the convexity is hypolordotic. After placement of the contoured rod into the hooks, it is rotated, thereby derotating the spine, and the frontal deformity in effect reconstitutes a more normal sagittal contour.[84] A device for transverse traction (DTT) connects the rods and forms a rectangular construct that increases rigidity, particularly in axial rotation.[56]

The various components of the CDI system are not unique: segmental open hooks (Wisconsin compression apparatus), compression and distraction rods, pedicular hooks (Harrington), and transverse linkage (Luque) already had been used. The fundamental difference was the incorporation of these components into a surgical technique, to apply three-dimensional corrective forces and provide immediate stability in the absence of external immobilization, both with acceptable neurologic risk.

Cotrel et al[83] reported on the first 250 patients who received CDI. Their series included patients with spinal deformity secondary to idiopathic, degenerative, and neuromuscular etiologies. No patient had postoperative external immobilization. Average frontal correction was 66%, with improvement of the sagittal contours. Correction of flexible curves averaged 75% to 78%. Less than 5% loss of correction was observed at long-term follow-up. No instrumentation failures were reported. There were two patients with major neurologic complications; one had osteogenesis imperfecta, and the neurologic compromise resolved, and the other had kyphosis (this patient was observed postoperatively as having canal encroachment by two hooks around the same lamina). After the authors' series had been expanded to 600 patients, they concluded that it was the ''instrumentation of choice'' for most spinal deformities (Fig. 1).

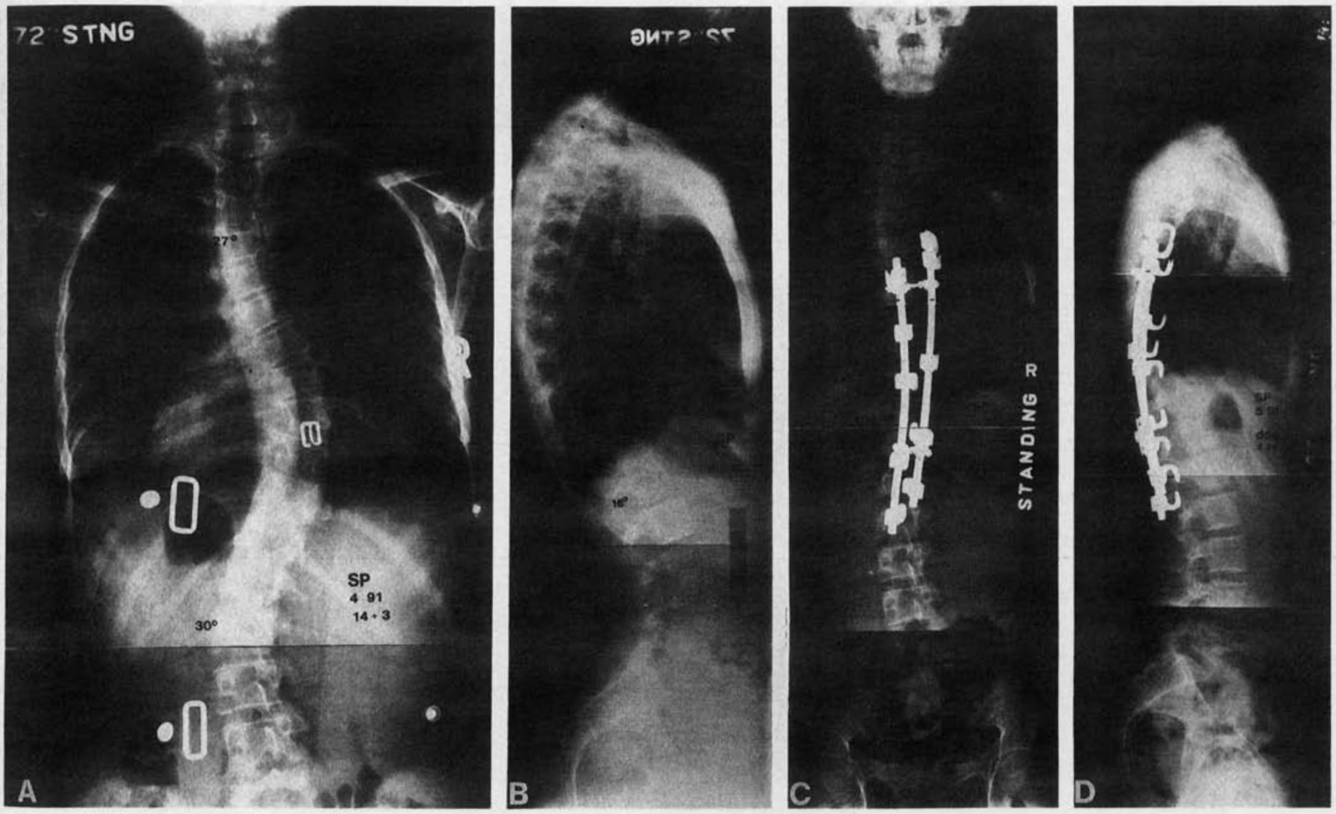
Spinal surgeons around the world have applied CDI techniques for deformity, trauma, and degenerative conditions. Through this extensive experience, the benefits and disadvantages of the system have become apparent. Immediate rigid fixation does allow most young patients to be without postoperative immobilization; a benefit that was not universally achieved with other fixation systems.[85,86] Frontal curve correction is generally as good as alternative systems,[87] but sagittal curve correction, especially thoracic hypokyphosis and lumbar hypolordosis, is better corrected. Although as much as 40% apical derotation has been reported previously (Shufflebarger HL. Presented at the Second International Meeting on Cotrel-Dubousset Instrumentation, Paris, France, June 10, 1985), other investigators have concluded that less derotation may occur or may be focused at or beyond the ends of the instrumentation (spinal–pelvic and cervico–thoracic rotation) (Transfeldt E, et al. Proceedings of the Scoliosis Research Society, 1988; Wood KB, et al. Presented at the 85th Annual Meeting of the American Academy of Orthopaedic Surgeons, March 7–12, 1991). Others have questioned the effect of vertebral rotation on the rib deformity (Closkey RF, et al. Presented at the Annual Meeting of the Scoliosis Research Society, Baltimore, MD, 1988).

There are several disadvantages of CD instrumentation. First, it is technically demanding to implant. This plus overzealous attempts to correct deformity with this powerful technique may account for the three- to fourfold (≤3%) increase (when compared with Harrington rods [Morbidity Report. Presented at the Annual Meeting of the Scoliosis Research Society, 1987 (Baltimore, MD), and 1988 (Vancouver, BC)]) in neurologic injury reported to the Scoliosis Research Society in 1987.

Second, the instrumentation is bulky and may become prominent under the skin. It also is significantly more costly per application.

Finally, truncal decompensation, or imbalance, may occur after instrumentation of certain thoracic curves. Most of these problems are experience related. As surgeons become better versed in the correct application of CDI, understand its limitations, and redefine hook patterns and fusion levels to avoid decompensation, the benefits may truly make this, or similar variable hook–rod constructs, a ''universal instrumentation.''

Despite improvements, fixation to the sacrum at the end of a long fusion remains problematic. The original Harrington sacral laminar and alar hooks were subject to fre-



Figs. 1A–1D. Adolescent idiopathic scoliosis. This 14-year-old perimenarchal girl presented with moderately severe progressive scoliosis, the major curve measuring 43° at the time surgery was elected (A and B). (C and D) Postoperative films show correction to 20° after posterior spine fusion with Cotrel–Dubousset instrumentation.

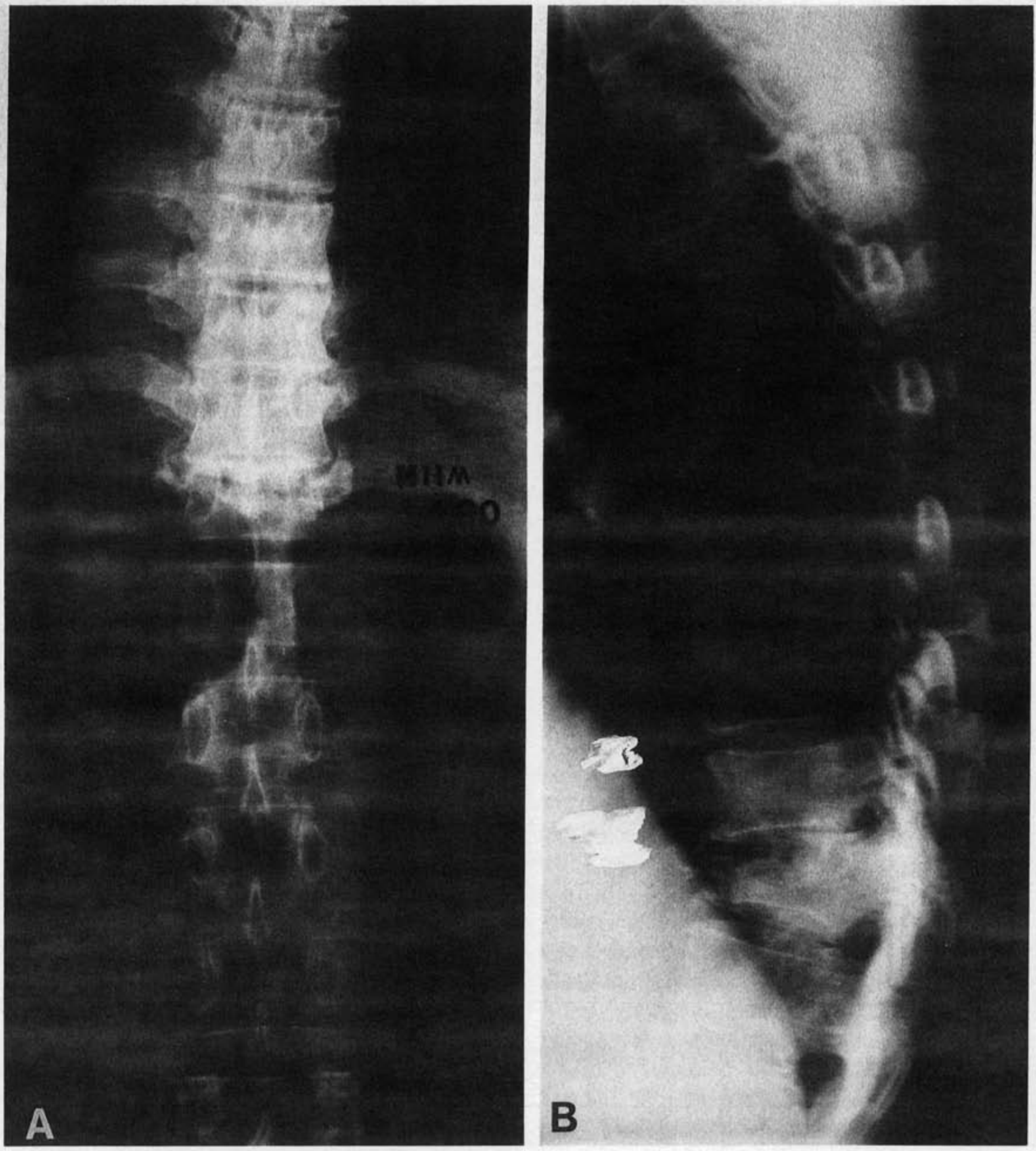
quent dislodgement. The weakness of the sacral lamina limits the practical placement of hooks at S1.[43] Sacral screws offered an improvement over hooks, but are subject to pullout due to lack of adequate purchase in the relatively osteopenic sacral bone. Divergent sacral screws placed at S1 and S2 increase fixation strength, but failures are still reported (Barnard H, et al. Presented at the 24th Annual Meeting of the Scoliosis Research Society, Honolulu, HI, September 24–27, 1991).

In obtaining fixation to the pelvis combined with Luque's sublaminar wiring technique, Allen and Ferguson[88] advocate the placement of pre-bent rods across the sacroiliac joint and continuing them between the tables of the ilium. The "Galveston" technique is particularly useful in patients with neuromuscular scoliosis, the patient group most commonly seen with pelvic obliquity or other indications for fusion to the pelvis.[89]

Because of the problems of sacral fixation in nonneuromuscular curves, surgeons have combined CDI-type hook–rod configurations with Galveston fixation to the pelvis. The reported complication of sacroiliac joint pain may make this technique less attractive for ambulatory patients. Divergent sacral screws, iliosacral screws, and Galveston technique are among the various techniques that are currently used at the end of long fusions to the sacrum.

Anterior Thoracolumbar Instrumentation

Although Harrington instrumentation and its modifications corrected scoliosis curves through distraction on the concave side, the recognition that compression or shortening of the convex, or longer side, also would result in curve correction led Dwyer[90,91] to devise a system to accomplish this. He elected to apply compressive forces to the convex side via an anterior approach, so that the instrumentation would be attached to the vertebral bodies rather than the posterior elements. A titanium screw was devised which attached through a staple to the vertebral body. The screws were linked by threading a cable through the screw heads. After the disc material had been removed from each interspace to be fused and appropriate bone graft placed (usually morcelized rib), screws were sequentially added to the cable and the cable tightened with a special tensioning device. After adequate compression had been applied, the screw head was then crimped to the cable to prevent loosening. Of importance as well, was that all implant edges were rounded



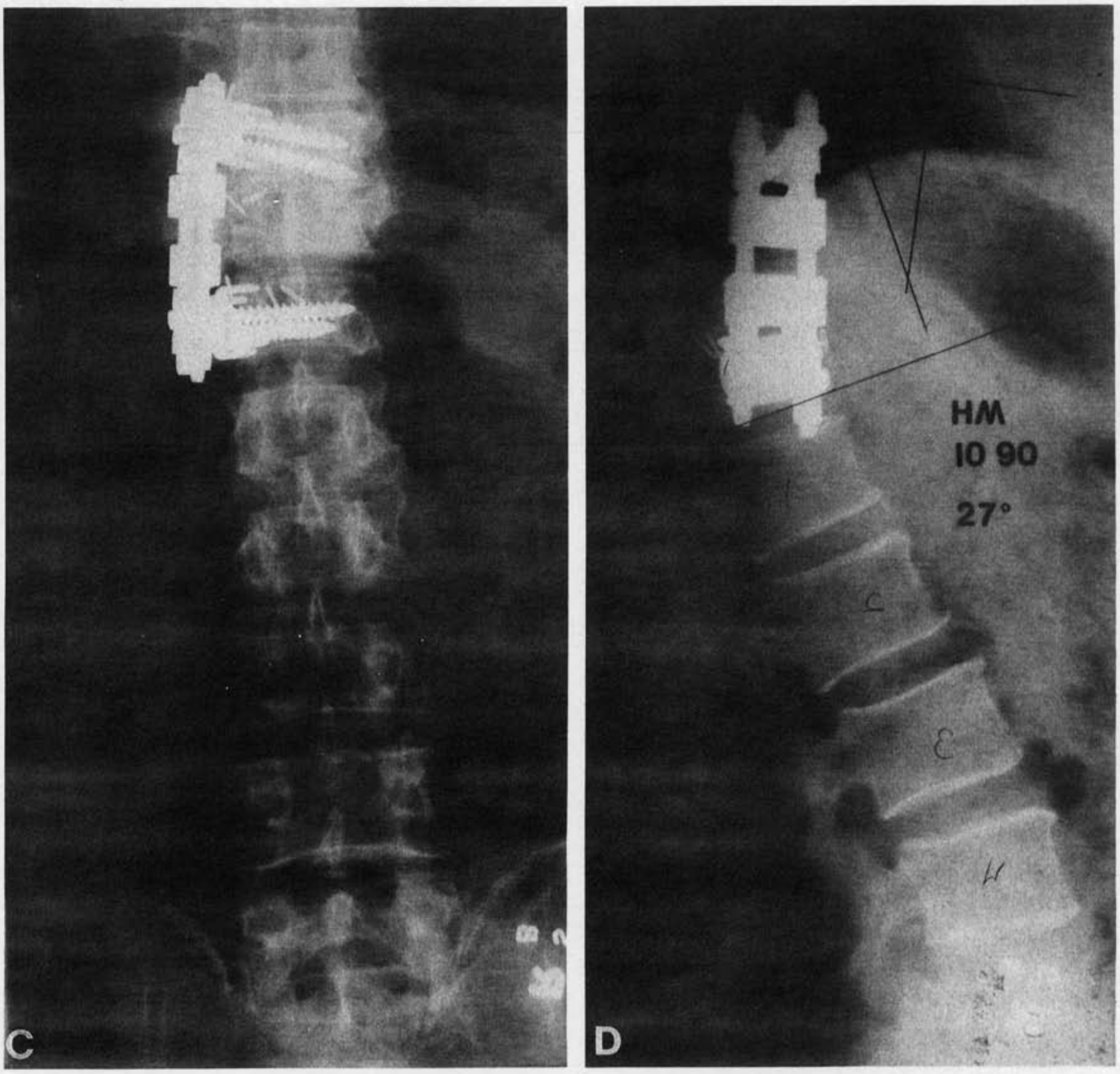
Figs. 2A–2D. Use of the Kaneda device (AcroMed Corp., Cleveland, OH) for fractures. This 35-year-old man suffered a T11 burst fracture with incomplete neurologic injury. (A and B) Preoperative films. (Fig. 2 *continues.*)

to decrease the risk of damage to the overlying viscera and vascular structures.[90,91]

In 1978, Zielke and Stunkat[92] reported on his modification of Dwyer's system to a Ventral Derotational Spondylodesis (VDS) System. They proposed using a semi-rigid, threaded rod in place of Dwyer's cable. This permitted the use of nuts for incremental correction, and, more important, the temporary application of a derotation outrigger device, which permitted correction of the rotational component of the patient's deformity.[91,93] One of the criticisms of the Dwyer system was that it tended to bring the lumbar spine into kyphosis. However, proper application of the system used by Zielke and Stunkat to a posterolateral position on the vertebral bodies, as well as application of the derotator and its use of three-point fixation, permitted lordosization to occur with the derotation maneuver.

The instrumentation is best applied in the lumbar and lower thoracic spine, because the size of the vertebral bodies in the mid- and upper-thoracic spine precludes placing these relatively large screws and/or applying significant forces.

The Dwyer and Zielke devices had the advantage of per-



(Fig. 2. *continued.*) (C and D) The patient underwent an anterior decompression, fusion, and stabilization with Kaneda instrumentation. Notice that, technically, the screws were placed too anteriorly resulting in incomplete correction of the patient's kyphosis.

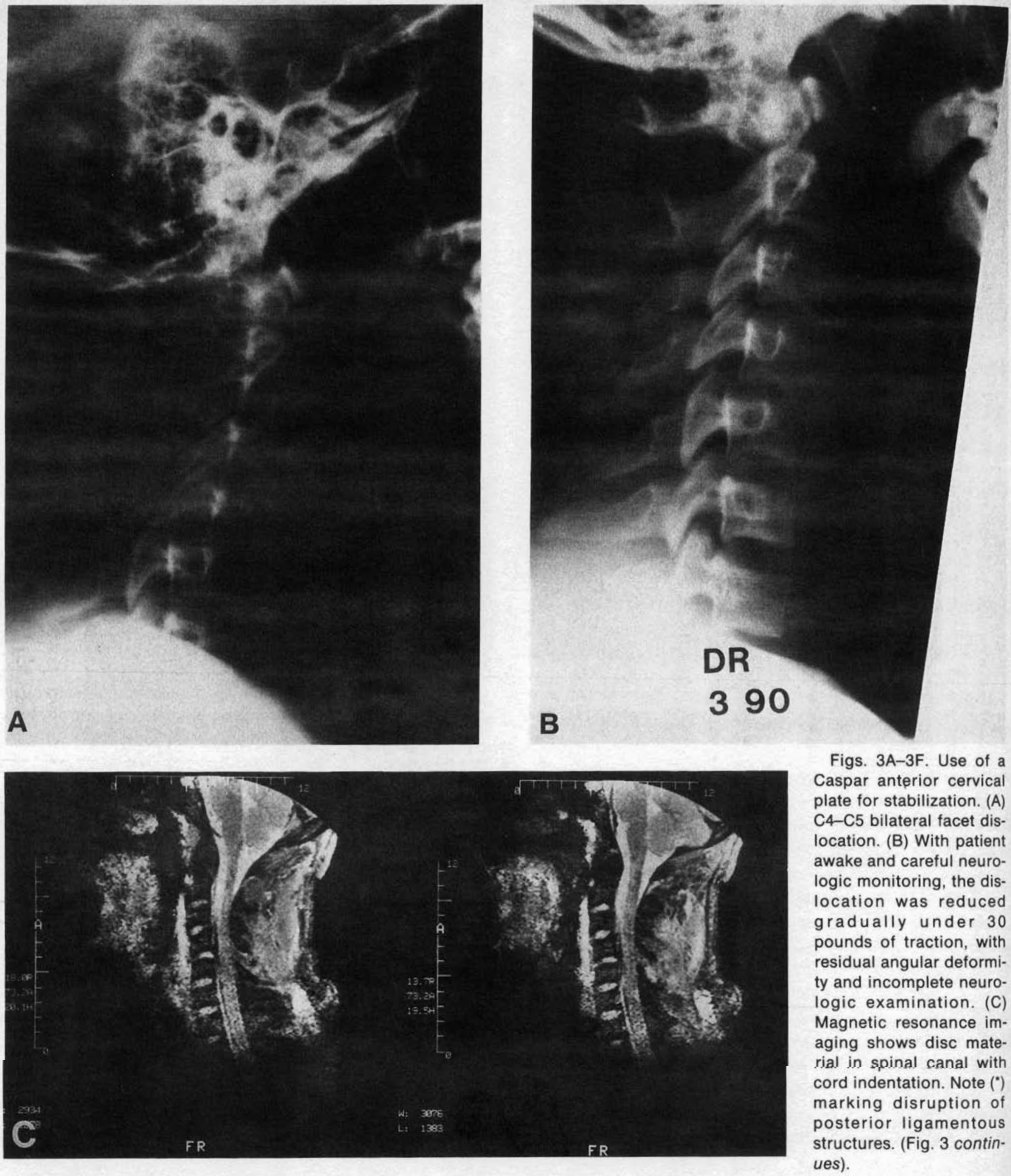
mitting more correction than was usually possible by Harrington instrumentation—up to 70% for adolescent lumbar curves[94]—as well as requiring a shorter area of fusion.[95,96] The latter is especially relevant for the lumbar and thoracolumbar curves where it is preferred to preserve the greatest number of motion segments below the curve, because lower levels of fusion appear to increase the risk of later degenerative changes below.[79]

Disadvantages of the system include the need to perform a retroperitoneal or thoracolumbar approach, not always a routine procedure for spine surgeons, and the risk of damage to visceral, vascular, and neural (sympathetic) structures.

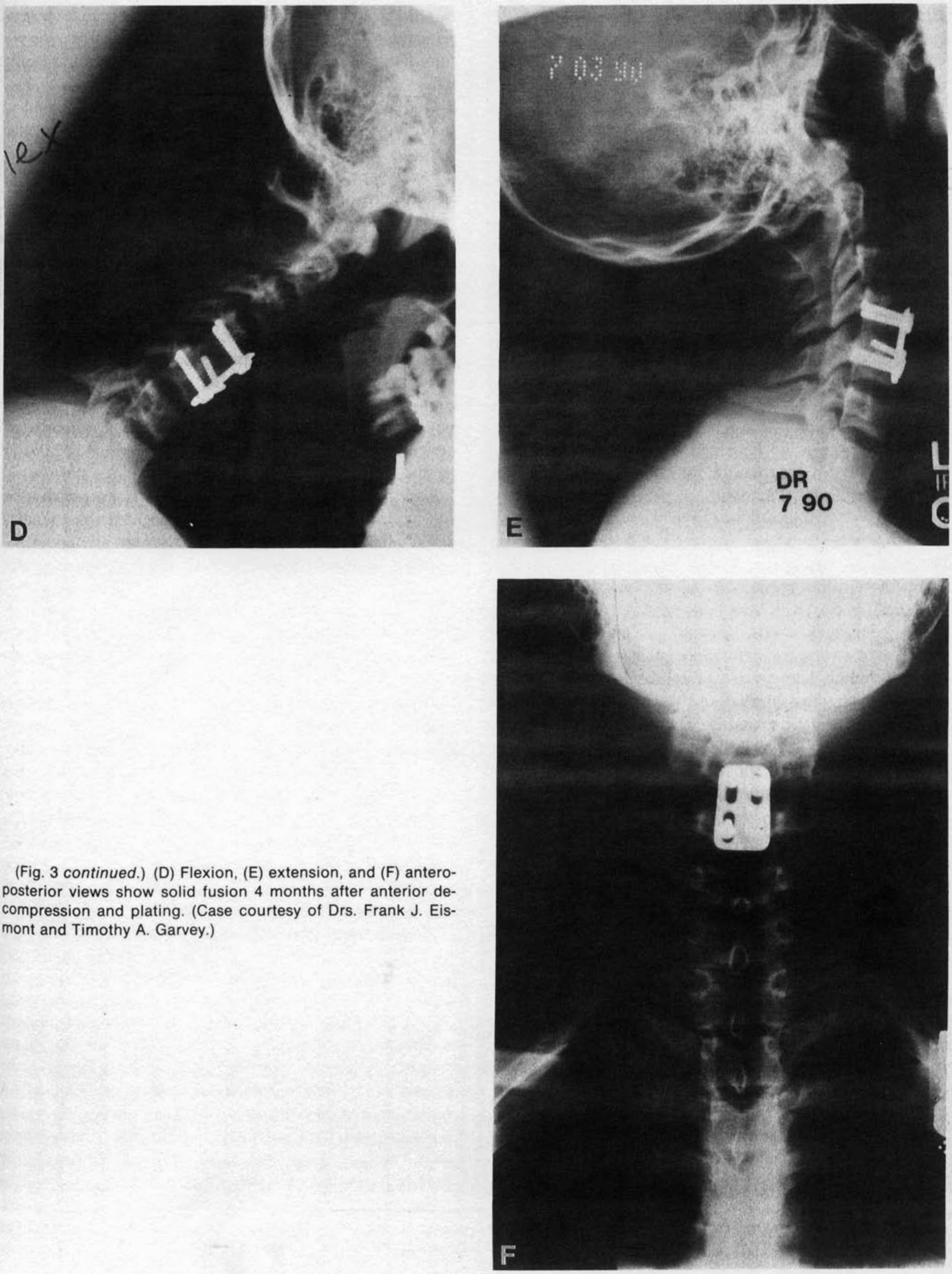
The Zielke system, although still used by some for idiopathic lumbar and thoracolumbar curves, is currently most commonly indicated for those with absent or deficient posterior elements, such as myelomeningocele or postlaminectomy; certain neuromuscular curves, such as cerebral palsy, particularly if lordosis is associated; or other rigid paralytic curves, where more correction is needed than that which would be obtained with an anterior release with fusion and posterior fusion alone.[72,95,96] For these curves, it may be used in conjunction with posterior segmental (sublaminar) instrumentation.

As with posterior instrumentation, surgeons attempted to expand the uses of anterior instrumentation to other situations where stabilization was required, particularly in the treatment of fractures. Burst fractures, one of the most frequent fracture patterns in the thoracolumbar spine, often have retropulsed bone impinging anteriorly on the neural elements. Many have advocated posterior distraction against an intact posterior longitudinal ligament, permitting indirect reduction of the fracture fragments, or ligamentotaxis. However, this indirect reduction was variable and only useful in the acute period. This meant that many patients who required decompression of a compromised spinal canal required an anterior decompression (ie, vertebrectomy, followed by prolonged bracing or a posterior fusion and instrumentation) to lend adequate stability to the now-further destabilized spinal column.

The Zielke instrumentation, although more rigid than the original Dwyer cable, did not appear to provide adequate stability in patients with unstable spines, and, in their early application to spine fractures, unacceptable rates of pseud-



Figs. 3A–3F. Use of a Caspar anterior cervical plate for stabilization. (A) C4–C5 bilateral facet dislocation. (B) With patient awake and careful neurologic monitoring, the dislocation was reduced gradually under 30 pounds of traction, with residual angular deformity and incomplete neurologic examination. (C) Magnetic resonance imaging shows disc material in spinal canal with cord indentation. Note (*) marking disruption of posterior ligamentous structures. (Fig. 3 *continues*).



(Fig. 3 *continued.*) (D) Flexion, (E) extension, and (F) anteroposterior views show solid fusion 4 months after anterior decompression and plating. (Case courtesy of Drs. Frank J. Eismont and Timothy A. Garvey.)

arthrosis were encountered,[97] as well as screw pullout.[98] In the late 1970s and early 1980s, Kaneda et al,[97] Dunn,[98] and Kostuik,[99,100] began independently to develop anterior instrumentation systems for use with thoracolumbar spine fractures.

Dunn[98] experimented with several systems and eventually was satisfied with a curved plate and staple, which were each connected to the vertebral body via screws. The thick plate and staple interlock with a spring clip and are connected to each other with two rods. His biomechanical data suggested that the two screws should be separated from each other by an arc of 60° for optimal stability. He suggested that the spine be approached from the right side, where the low pressure venous system would be in closer proximity to the implants than the aorta, and that a Teflon pad be used between the implants and the vascular structures if contact could not be avoided.[98] Despite these cautions, there were reports of vascular erosion with catastrophic results from these relatively high-profile systems; the Dunn device is no longer used (Brown LP, Bridwell KH, Holt RT. Presented at the Scoliosis Research Society Meeting, September 18, 1985).

Kostuik[99,100] combined the Dwyer screw and a solid Hall rod with a new screw used with ratcheted Harrington rods. The latter permitted correction of kyphosis, with the construct further strengthened by the addition of the Dwyer screw/Hall rod (which was later modified to use a Harrington compression rod). Kostuik[99,100] found no cases of nonunion or instrumentation failure in his initial series of 31 patients, and his later series of 80 patients noted two nonunions and 11 screw breakages.

The instrumentation used by Kaneda et al,[97] which is currently gaining in popularity, also requires two screws placed in each vertebral body. However, their configuration is trapezoidal with the more widely separated screws placed more anteriorly on the vertebral body. These screws are placed through staples on the lateral aspect of the vertebral body. Threaded rods link the screws, and a distractor and/or the setting nuts can be used to correct any kyphotic deformity. More recently, a rigid cross-link has been added to the instrumentation, further strengthening the construct (Fig. 2).

Biomechanical testing shows the Kaneda device to be stronger than the Kostuik device and other systems in resisting flexion and lateral bend[61] (Mann KA, et al. Presented to the Orthopaedic Research Society, January 21, 1987).

Pedicle Screw Instrumentation

Compared with anterior vertebral body or posterior element fixation, segmental spinal purchase through transpedicular instrumentation provides the most biomechanically rigid restraint to spinal motion in flexion, extension, and torsion.[101] Other biomechanical studies have shown that, in an unstable spine model, pedicular fixation is more rigid than similarly tested hook–rod devices or segmental instrumentation.[20] Moreover, pedicle screw systems generally require fewer instrumented segments for adequate immobilization, a desirable characteristic in the lumbar spine. This, as well as the larger pedicle diameter found in the lumbosacral spine, results in the increasing use of interpeduncular screw fixation in the lumbar spine rather than elsewhere.

Purchase in the pedicle depends on several factors. The major (outer) diameter of the screw is important in optimizing the metal–bone interface (Transfeldt E, et al. Proceedings of the Scoliosis Research Society, 1988). This factor must be balanced by the observation that large screws traversing the pedicle may penetrate the inner cortical wall adjacent to the neural structures. Studies have shown that, even in experienced hands, cortical breakout can occur in 5% of pedicle screw placements and is associated with a 3.2% root injury rate (Luque ER. Proceedings of the Scoliosis Research Society, 1987). Recent studies on the morphology of the lumbar pedicles have enabled orthopaedic surgeons to better understand the techniques and hazards of pedicle screw placement.[102]

Bone mineral density and the depth of screw penetration also are important factors in determining fixation strength. Coe et al[103] have shown that pedicle screws are less effective than laminar hooks in resisting failure by axial pullout in osteoporotic bone. In the lumbar spine, where bone mineral density is usually adequate to hold most screws, the screw need only traverse the pedicle and pass into the body for a short distance. Although purchase in the anterior cortex does increase the pullout strength of the screw,[104] the enhanced fixation is offset by the associated risk of damaging neurovascular and visceral structures lying anterior to the vertebral body. Screw fixation in the sacrum, where relative osteopenia compromises bone holding ability, may require careful penetration of the anterior cortex. Radiographic studies illustrate the problems with assessing the true depth of screw penetration with routine anterior–posterior and lateral radiographs.[105]

Krag[105] credits Roy-Camille with the popularization of pedicle screw fixation in the early 1970s. Three categories of pedicle screw systems are used today: screw–plate devices, fixateurs, and screw–malleable rod devices.

Screws connected to slotted plates (Steffee) or plates with holes (Roy-Camille) comprise the first group. Although excellent rigidity is obtained, these devices cannot produce compression or distraction forces or allow for significant screw–plate angular adjustment. Colinear placement of the pedicle screws and accurate plate bending are required for screw–plate connection. Micromotion between the screw and plate lead to fatigue fracture at the screw–nut junction of the early Steffee devices, but this problem appears to have been resolved with the newer designs.

The second group of pedicle screw systems comprises the internal fixators (Vermont Spinal Fixator,[105] AO Fixateur Interne,[106] Posterior Segmental Fixator,[81] and Edwards

Device), and external fixators.[107] These are characterized by Schantz-type screws connected to rods with multiplane adjustable connectors. Distraction forces can be exerted before tightening the connector. Fixators are generally less rigid than screw–plate devices, and late recurrence of deformity has been reported.[81,108] Problems with pin tract infection and poor patient acceptance have limited widespread application of external fixation of the spine.

With the screw–malleable rod devices, there is a direct connection between the pedicle screw and a semi-malleable rod. These devices are represented by the Wiltse and Puno devices[109] (Puno RM, et al. Proceedings of the Orthopaedic Research Society Annual Meeting, San Francisco, CA, 1987). Semi-malleable rods result in less stiffness and more load sharing than screw–plate instrumentation. Although lumbar spinal instrumentation has been shown to increase fusion rates (Kornblatt MD, Jacobs RR. Presented at the 12th International Society for the Study of the Lumbar Spine, Sydney, Australia, April 14–19, 1985), the influence of less stiff implants on the quality of bony fusion currently is being investigated. There is the theoretical possibility that less rigid fixation may decrease the degeneration of adjacent segments, which may be observed with rigid devices.[110]

Variable hook–rod systems also permit the use of screws as desired, for example at the lower end of the instrumentation. This clearly adds to their versatility, because the specific configuration needed can be applied according to the nature of the deformity being addressed.

Posterior Cervical Instrumentation

The choice of anterior versus posterior instrumentation in the cervical spine should be based on the type of lesion treated, the goals of the surgery, and the technical experience of the surgeon. Traumatic injuries with primarily posterior ligamentous and bony disruption are best treated with posterior instrumentation and bone grafting. Neurologic compression in the cervical spine from retropulsed bone or angular kyphosis may require anterior decompression which may be combined with anterior or posterior instrumentation or postoperative halo fixation, depending on the specific fracture pattern. In highly unstable lesions, as may be found in congenital or neoplastic processes, stability only can be produced through both anterior and posterior surgical approaches.

Intersegmental wires placed either through the spinous processes (Rogers technique[111]) or around the lamina (Brooks technique[112]) are a proven method of posterior fixation in the cervical spine. The addition of structural corticocancellous grafts to the construct significantly increases the rigidity, including its resistance to anterior–posterior translation. Biomechanical studies suggest that techniques such as double-looped wire, twists instead of knots, and bilateral versus single loops increases the effective strength of the implant and potential stability of the implant-bone construct.[113]

As with the subcervical spine, the risk of placing sublaminar wires is considerable. Whitehill et al[114] documented a 20% neurologic complication rate when sublaminar wires were used in the canine cervical spine. Although the space available for the spinal cord is relatively large in the area of the normally aligned atlanto-axial spine, the canal narrows in the subaxial spine. The passage of wires in a relatively narrow space adjacent to a traumatized and often edematous cord makes sublaminar wiring less than ideal after trauma.

Posterior wiring produces a tension band that is effective in resisting flexion forces. The Halifax clamp also provides a tension band by coapting adjacent laminae. Hook–plate devices (AO–Magerl[107]) combine the benefits of screw fixation cranially with laminar hooks caudally to resist flexion. Coe and co-workers[115] have shown through biomechanical testing of interspinous wiring, sublaminar wiring, and AO hook plate fixation, that no significant difference in flexural or torsional stiffness was observed. Based on these findings, the authors caution that the added risk of sublaminar wires is not justified.

Sublaminar and spinous process wiring require intact posterior elements. In iatrogenic (laminectomy) or congenital (spinal rachitis) absence of the posterior elements, alternative methods for stabilization must be used. Facet wiring with segmental fixation to a structural dowel graft (fibula, rib, or steel rod) has been used in this situation. Although this technique adequately immobilizes the spine to flexion and extension forces, Pelker et al[116] have shown that facet fusion and wiring may leave the spine unstable to rotational forces.

Posterior cervical screws and plates more effectively control flexion, extension, and axial rotation forces than wiring techniques. Popular in Europe, the use of posterior plates and screws has not been used as extensively in North America. Roy-Camille et al[117] have illustrated the importance of directing subaxial screws laterally into the lateral masses to avoid the midline neural structures and the anterior vertebral artery. Special attention to accurate screw placement is essential in the axis because of the unique morphology of the lateral masses and the serpentine course of the vertebral artery.

Difficult cases may require specialized instrumentation. Atlanto-occipital fusions performed for the treatment of basilar impression due to rheumatoid arthritis are facilitated by the application of long, L-shaped plates that buttress the occiput and resist further cranial settling. Whether this device improves the results of occipital–cervical fusion compared with simple wiring has not been demonstrated.[118] The screw–plate method has been applied extensively to occipital–cervical fusions by Roy-Camille and a select group of investigators; however, the efficacy and safety of these techniques are not widely proven.

Hook–rod devices such as Harrington instrumentation and CDI have been applied to the cervical spine in certain cases. The benefits of distraction, compression, and rigidity provided by these devices must offset the disadvantages of possible hook encroachment in the canal and their bulkiness. Their application should be limited to those cases where more traditional methods would not be equally effective.

Although the addition of polymethylmethacrylate gives immediate rigidity to a bone–metal construct, bone cement may be impractical for routine use because it increases the likelihood of infection, long-term fixation failure,[119] and the incidence of wound problems. In the patient with severe rheumatoid involvement with poor bone stock, limited use of polymethylmethacrylate may give early stability for those patients who cannot tolerate halo immobilization. Caution should be exercised that small quantities of cement be used (to decrease wound healing problems secondary to bulk and tissue necrosis) and that a careful bony fusion is performed.[120] Patients with neoplastic involvement of the spine and limited life expectancy may benefit from the symptomatic relief afforded by immediate stabilization with polymethylmethacrylate-augmented instrumentation.[121]

Anterior Cervical Instrumentation

Analogous problems to those in the thoracolumbar spine need to be addressed for those surgeons treating cervical spine injuries. Here again, it is often preferred to decompress the spinal cord via an anterior vertebrectomy[122–124]; however, the majority of cervical injuries occur by a compressive flexion mechanism[5] and include posterior ligamentous disruption as well. As with thoracolumbar fractures, simply performing a vertebrectomy and strut graft in such patients can further destabilize the spinal column, resulting in neurologic deterioration or progressive kyphotic deformity.[125–127]

The anatomy of the cervical spine, because of the presence of the vertebral artery laterally, necessitates direct anterior application of anterior instrumentation. Initially, plates of various designs were implanted with good early results with respect to stability.[128,129] However, longer results of follow-up showed that many of the screws had loosened over time. It became apparent that screw fixation through only the anterior vertebral body cortex—surgeons were naturally wary of placing screws through the posterior vertebral cortex with the attendant neurologic risk—was not adequate fixation. Screw loosening or backing out endangered the nearby viscera, including the carotid artery, esophagus, and internal jugular vein.

The Caspar plate system appears to prevent screw back out.[130,131] This instrumentation includes a distractor that can be placed on distractor screws placed in the vertebral body. Distraction after vertebrectomy or discectomy permits placement of a strut graft, either iliac crest or fibula, with adequate correction of kyphosis; compression on the strut then can be performed to firmly inset the strut. More important, the drill guide can be adjusted to permit drilling to a depth 1 mm less than the measured depth of the vertebral body anterior–posterior diameter; although fluoroscopic control is recommended for drilling, tapping, and screw placement. This appears to be a reliable, reproducible method of obtaining bicortical screw penetration while minimizing the risk of dural or spinal cord damage (Fig. 3).

Biomechanical studies have compared several posterior wiring techniques as well as the Caspar plate system in compression, flexion, extension, and rotation.[115] These suggest that anterior Caspar plates are not adequate in reestablishing the stability of an intact spine in any mode of testing except extension, in contrast to posterior techniques. However, the good results published from various centers[132,133] (Garvey TA, Roberti LJ, Eismont FJ. Poster presented at the Meeting of American Spinal Injury Association, Seattle, WA, April 1991) suggest that with appropriate postoperative bracing and activity precautions, anterior plating may be sufficiently strong to permit healing with minimum loss of correction and without the need for a posterior fusion in cases where an anterior decompression is needed in the face of posterior ligamentous disruption.

Recently introduced is the AO cervical locking plate. This system utilizes a second screw to lock the primary titanium screw to the plate. The primary screw, which only penetrates the anterior cortex, is plasma-sprayed and fenestrated to permit bone ingrowth, thereby preventing screw backout. Early clinical results are encouraging; the system may permit the advantages of anterior plating without the risk of screw encroachment into the canal.

Conclusions

Greater understanding of the implications of surgical interventions, coupled with advanced techniques and devices, offer surgeons greater expectations for providing their patients with improved quality of life. Clearly, many refinements in the design and implementation of spinal implants are necessary to enable the spine surgeon to continue to expand this knowledge and meet these challenges.

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