44. Surgical fusion of the spine to the sacrum

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INTRODUCTION

Problems at the lumbopelvic junction date back to the time when humans first stood upright. Even with the advent of modern medicine, the complex anatomy of this region, including the proximity of nerves and other vital structures, has frustrated attempts at satisfactory surgical treatment. While technological advances over the years have improved the success rate of lumbosacral arthrodesis, the search continues for more sophisticated methods that will restore not only general function, but satisfactory motion as well. The enormous forces and long lever arms in this region make arthrodesis difficult to achieve. Solutions to the problems of lumbosacral fusion have emerged only in recent decades as advances in implant design, fusion technique, and anesthesiology have made it possible to achieve consistent success when fusion at the lumbosacral junction is undertaken.

THE ROLE OF FUSION

The decision to perform spine surgery is valid if, and only if, the patient's problem (1) can be defined anatomically and (2) can be solved by neural decompression, tumor excision, correction of deformity, stabilization of unstable segments, or a combination of these procedures. The indications to perform surgery in certain lumbar degenerative disorders is made more difficult owing to the frequent poor correlation between imaging studies and clinical symptomatology, as well as the absence of a universally accepted clinical definition of lumbar spinal instability. In any spine surgery, the last step before closing the incision is to evaluate and treat possible spinal instability, which may be obvious or occult. While certain procedures are performed to correct instability, others, such as extensive decompressive procedures, may create instability. In both cases, the spine must be stabilized prior to closing the incision. Fusion is the most popular means of stabilization. Theoretically, methods other than fusion, for example, muscle strengthening or implanting artificial discs or ligaments, can be used to treat instability. A surgically performed fusion in a patient, however, is evidence that a surgeon encountered a prior instability. Fusion can be employed to treat a single motion segment or the entire spine, depending on the length of the unstable section and considerations of spinal balance. The instability may be of an acute nature, arising from trauma, or it can be caused by surgical decompression. Instability can be chronic, as caused by a degenerative process, or it can be a postural instability, as evident in deformities. In general, fusion is a comprehensive solution to instability as it eliminates pathological motion between neighboring elements. The fusion mass consolidates and includes spinal elements between which a 'fracture situation' has been created, and bone surfaces are permitted to heal into a single unit. It is important to understand that a fusion cannot correct a deformity and that a fusion cannot provide decompression of the spinal canal. A fusion is only a consolidation of the existing situation at the end of a surgical procedure.

THE ROLE OF INSTRUMENTATION

There is a consensus that the main role of instrumentation is to facilitate bone healing by splinting the fusion site. However, there is no consensus regarding the practice of correcting deformities using instrumentation. There is also no consensus regarding non-instrumented in situ fusions that address spinal pathology without attempting anatomic realignment or reduction. The role of instrumentation as a splinting device to provide stable fixation until fusion occurs is well established. Instrumentation permits realignment of the spine during surgery and minimizes spinal motion that may decrease the success of fusion. Fusion of the spine to the sacrum is a considerable mechanical challenge. It requires counteracting the lever arm of the trunk above the pelvis. The bone implant construct achieved in surgery must have sufficient stability to resist collapse under a multitude of loading conditions until fusion occurs. There are currently many techniques and implants available to the spine surgeon that may be utilized to address various types of spinal deformities and spinal instability.

SPINAL STABILITY

The stability of the spine can be predicted if the mechanical behavior is known. The determinants of mechanical behavior vary between individuals. Therefore, the prediction of response to abnormal loading is impossible. A universal definition of instability that includes all variables of mechanical behavior does not exist. The stability of the spine is affected by restraining structures that, if damaged or lax, will lead to altered equilibrium and ultimately instability (Gertzbein et al 1985, Nachemson 1985). A spinal column that is able to maintain alignment when subjected to physiological loads in any plane while protecting the neural elements is considered stable. If displacement of the spinal column is likely to occur, the spinal column is considered unstable (Purcell et al 1981). Most definitions of stability allude to the effect of dynamic loading as well as the presence of deformation over time (Haher et al 1989). Unfortunately, there is no way to restore any kind of dynamic stability at the level of the motion segment. Common practice is to fuse the affected motion segment, sacrificing its mobility altogether, in order to restore the function of the entire spinal column.

PRINCIPLES OF STABILIZATION

Surgical stabilization of the spine may be considered to occur in two stages. In the first stage, a 'fracture situation' is created during surgery in which adjacent bone surfaces are decorticated, bone graft is applied, and spinal instrumentation or external mobilization is utilized to decrease mobility at the surgical site. The second stage begins following surgery and consists of the cascade of events involved in the poorly understood biologic process of fusion consolidation. The surgeon's influence over this process includes the use of meticulous operative technique, selection of the location for fusion (anterior or posterior), as well as the selection of appropriate spinal implants that will adequately support the spine until fusion occurs. The act of stabilization starts, by definition, at an unstable stage that is caused either by the underlying pathology or by the surgeon. The unstable site constitutes a gap in the continuity of a normal functional structure and must be treated in a way that permits growth of a bony bridge across this region. Understanding the mechanics of the spine is crucial in determining exactly where this gap exists. Haher et al (1989) demonstrated that a localized site of mechanical damage to one of the columns of the spine changes the location of the instantaneous axis of rotation (Haher et al 1989). The existence of an axis of rotation in an abnormal location is a sign of instability and may warrant correction. Regardless of how one defines the spinal columns, it is important to augment the unsound column(s) and thus regain the mechanical stability of the spine. Modern surgical technique and technologically advanced implants permit short fusions localized to the unstable columns.

PRINCIPLES OF CORRECTION

Although many revolutionary ideas can be found in Harrington's writings, the posterior system he introduced was designed to treat deformities in the coronal plane. The scoliotic spine was fixed at the end vertebrae with hooks, and distraction was applied through a ratcheted rod that stretched the spine between these hooks. The rod and hooks served as an internal splint until fusion occurred and the construct was generally supplemented by external immobilization with a cast or brace. In an attempt to improve on problems with hook dislodgement and eliminate the need for postoperative external immobilization, Luque developed the sublaminar wiring technique. This technique provided correction in the coronal and sagittal planes via segmental control with wires. It provided for multiple points of fixation, which enhanced deformity correction and decreased the risk of fixation failure. Hybrid methods that combined the techniques of Harrington and Luque evolved and included the Wisconsin construct, with or without Drummond buttons, as well as the use of square-ended rods and special hooks, as introduced by Moe.

Although Wisconsin or 'Harri–Luque' techniques were safe in most hands, the fear of potential neurological injury by wires and the lack of positive reports in the literature led to a search for alternative methods. Since its introduction, Cotrel-Dubousset (CD) instrumentation has become the 'gold standard' for posterior spinal fixation (Cotrel et al 1988). It provides for multiple points of fixation with hooks and avoids the need to place sublaminar wires. CD instrumentation permits correction in the coronal and sagittal planes. It permits kyphosing-distraction and lordotic-compression forces to act along the same rod as a means of simultaneously controlling coronal and sagittal deformities.

The premise that the derotation maneuver proposed by Cotrel and Dubousset realigns the deformed coronal spine into normal sagittal posture was not uniformly accepted. Subsequent studies have shown that the transverse plane 'derotation' achieved with this system is more global than segmental in nature. This led to the development of alternative approaches to achieving curve correction. The principle of maximum control over each affected segment is paramount in the operative correction of spinal deformities. The goal is translation of each vertebra into its desired position by connection to a rod that is prebent to the appropriate sagittal contour. Techniques of segmental fixation have evolved through the use of combinations of hooks, wires, and ultimately pedicle screws. Adequate ancillary instruments may provide efficient lever arms to augment the correction maneuver. This approach is best represented by the AcroMed Isola (Asher 1993) and Synthes Universal Spine Systems (Aebi 1983).

Another way is to place strong, stiff, but ductile rods on the spine and use the technique of in situ bending to bring the spine to the 'normal' contour. This technique accentuates placing the rods in such a way that, at the end of the correction maneuver, the center of rotation of the whole assembly, which is now in the rods, is as close as possible to the normal center of rotation. The ductility of the rod is crucial to the success of this kind of correction. This approach is promoted by Jackson (Jackson 1994).

Anterior approaches are also utilized for the correction of spinal deformities. In anterior approaches, correction is achieved first through obtaining flexibility as the spine is released via discectomy or osteotomy and subsequently realigned with implants. Global curve derotation as a correction maneuver is possible with the anterior approach. Local curve derotation may be better achieved with the anterior approach than with the posterior approach. Recently, rigid anterior implant systems have been introduced in order to be used as a tool in surgery for derotation, improve fixation strength, and decrease instrumentation failure and pseudarthrosis rates. Control over deformities may be achieved by resection of disc or bone in order to change the relative length of the spinal columns. Shortening the anterior column produces kyphosis; elongating it produces lordosis. Resection or insertion of a wedge can be utilized to align scoliosis or enhance correction of sagittal plane deformities. Structural grafts or implant spacers can be used to restore anterior column height and re-establish the normal relationship between vertebrae. If performed properly, restoration of disc space height provides indirect opening and decompression of neural foramina. Disc height can be restored by posterior lumbar interbody fusion (PLIF), anterior lumbar interbody fusion (ALIF), or a posterior maneuver utilizing a pedicular screw-based construct. The success of posterior pedicle screw-based constructs depends upon the presence of adequate anterior column structural support.

In certain spinal disorders, combined anterior and posterior techniques are required in order to achieve sufficient deformity correction, provide for adequate spinal canal decompression, and increase the likelihood or successful arthrodesis. Harms in Germany advocates the combined approach as the most efficient method of treating a wide variety of spinal problems based on the concepts of the posterior tension band and anterior load-sharing principles (Bohm et al 1990). A relatively thin posterior compression implant, combined with a solid anterior spacer, creates a construct in which 80% of the load is applied to the anterior column and 20% to the posterior column. The logical application of this concept is to the correction of kyphotic deformities and improving lordosis in cases in which it has been lost. A variation of the combined approach consists of an interbody fusion, which may be accomplished as either a PLIF or ALIF and stabilized by posterior instrumentation. In this approach, the purpose of the posterior fixation is to stabilize the interbody graft or cage and a formal posterior fusion is not performed.

In the most extreme and severe deformities, resection and decancellation procedures as advocated by Luque and Bradford may be required. These procedures create circumferential instability and permit subsequent spinal correction through shortening the spinal column. Such techniques permit correction of deformities that are not adequately treated by any other approach. Heinig has applied this concept of creating iatrogenic instability solely through the posterior approach in order to correct severe deformities, and has termed this the eggshell procedure.

ANATOMIC CONSIDERATIONS

The biomechanical situation at the lumbosacral junction does not favor fusion. Since the L5–S1 disc is positioned at 45° to the gravity line and is subject to shear forces, there are no direct natural compressive forces buttressing the fusion site. The lever arm on the fusion zone is enormous. External immobilization is cumbersome and frequently ineffective. With regard to anatomic considerations, two points must be stressed.

First, the lumbopelvic articulation not only includes the L5–S1 junction, but also consists of the distal lumbar vertebrae, the sacrum, and those parts in proximity to the sacroiliac joints (SIJs). It has an osteoarticular axis, is powered by musculofascial elements, and is traversed by neurovascular structures. The articulation has relationships with the neighboring anatomic regions and shares mechanical functions with the rest of the vertebral column (Louis 1985).

Second, the pelvis, as an intercalary bony structure between the spine and lower limbs, should be viewed as the 'pelvic vertebra'. It plays a major role in standing and sitting by adjusting balance in order to maintain the head optimally along the body's line of gravity. Three-dimensional posture is made physiologically possible by a chain of motion segments that permit self-adjusting erect posture in response to the effects of gravity on proprioception.

INDICATIONS FOR FUSION TO THE SACRUM

Trauma

Because of the unique anatomic features and mechanical characteristics of the lumbosacral junction, trauma at this site is infrequent. The lumbar spine requires fusion to the sacrum for trauma only in very specific situations where the integrity of the spinal column is grossly disrupted. Most sacral fractures are secondary to pelvic trauma and do not require fusion.

Tumors and infections

The indications for fusion are a function of the amount of destruction and instability caused by the underlying pathological process as well as the instability created in the procedure of spinal canal decompression. Because the spinal canal in the lumbopelvic region has ample space for neural elements, neurological damage of mechanical origin in the case of tumors and infections is rare. When neurologic symptoms do occur, these are typically manifest late in the course of the condition (Sucher et al 1994).

Degenerative disorders

Degenerative changes involving the lumbosacral spine can lead to pain, instability, and deformity.

A solid and balanced fusion that eliminates painful abnormal motion at the lumbosacral joint while restoring structural integrity may reduce pain, stabilize deformity, and improve overall function. Definitions of instability remain controversial.

Pelvic obliquity

Pelvic obliquity is one of a variety of conditions for which fixation to the sacrum may be recommended or even necessary. Pelvic obliquity occurs when the pelvic vertebra is tilted abnormally in the coronal, sagittal, or horizontal plane. Pelvic obliquity can be caused by suprapelvic, intrapelvic, or infrapelvic pathology, and may be fixed or non-fixed.

Spondylolisthesis

Spondylolisthesis remains among the most controversial indications for surgery. The controversy includes the decision when to perform surgery, the need for decompression, the need for instrumentation, the need for realignment, and the indications for circumferential fusions. Instrumented reduction of severe spondylolisthesis is considered to be among the most challenging types of spinal surgery.

FUSION TECHNIQUES

Non-instrumented fusion

Non-instrumented fusion techniques may be classified as:

- spinous process-related fusions
- interlaminar fusions
- posterolateral fusions
- interbody fusions.

The indications for non-instrumented fusion at the L5–S1 junction are limited, due to limited success (Apel et al 1989, Riley et al 1986). Adherence to the technical aspects of these procedures, specifically meticulous bone graft 'carpentry', is crucial to the success of this type of procedure. In the future, the need for internal fixation may be diminished, especially in cases where anatomic alignment is not the primary concern, if bone morphogenetic protein (BMP) and other agents for bone induction and conduction prove efficacious.

Instrumented fusion

Modern posterior spinal fixation systems consist of three basic elements:

- implants attached to the posterior spinal elements
- implants attached to the sacrum or pelvis
- longitudinal members connecting the posterior implants.

There are three basic options for gaining purchase upon the posterior elements of the spine: (1) hooks, (2) wires or cables, and (3) screws. A single hook permits control in one plane, in either a distraction or compression mode. Once the hook is engaged in a construct and combined with other hooks, various corrective forces can be applied to the spine across the entire instrumented segment. The introduction of hook 'claws' has greatly improved upon the fixation achieved by single hooks. Claw fixation combines upgoing and downgoing hooks across a single or adjacent level to achieve a strong mechanical interlock that greatly exceeds the fixation strength achieved by single hooks. Wires may be placed through the spinous process, underneath the lamina or in the subpars position. The amount of force that can be applied to a wire is less than can be applied to a hook owing to the smaller area of contact of the wire with the bone (Haher et al 1989). The introduction of flexible cables as an alternative to wires offers superior mechanical properties and provides a margin of safety owing to their ease of placement. Pedicle screws permit control of the spine in all planes and permit control of all three spinal columns from a single posterior approach.

Distal fixation options when fusion includes the sacrum are more varied. Hooks and wires are of limited value and are not widely used for sacral fixation. Various types of screw fixation techniques using either single or multiple screws to achieve purchase in the sacrum are the most commonly used techniques to achieve distal fixation. Sacral screws may be placed laterally into the sacral ala or medially into the sacral body toward the promontory to reach the upper endplate of the sacrum.

When maximal distal fixation is necessary, methods to enhance sacral fixation include

Galveston fixation, the Jackson technique, and iliosacral screw fixation. The Galveston method engages the ilium in the construct by utilizing a post that may consist of either a smooth rod or a screw. The post extends within the ilium and is placed in the column of bone located just above the sciatic notch. The Jackson technique enhances S1 screw fixation utilizing the concept of the 'iliac buttress' (Jackson & McManus 1993). The distal end of the rods pass through medially directed sacral screws and pass into the sacrum between its two cortices and under the wings of the ilium. Iliosacral screws are placed from the ilium into the body of the sacrum and engage at least three cortices in their path, thereby constituting a strong foundation for a spinopelvic construct. In most instrumentation constructs, the rods on each side of the spine are linked together with transverse devices in order to convert the unilateral rods to a quadrilateral construct of increased overall strength and rigidity. It is crucial to realize that the goal of the procedure is to achieve a successful fusion and that the spinal instrumentation construct will fail if fusion does not occur.

Anterior spinal fixation options are varied. Selection of the appropriate technique depends upon a variety of factors, which include:

- the type and location of spinal pathology
- the number of levels requiring surgical treatment
- the integrity of the anterior and middle spinal columns
- the goals of the surgical procedure.

The modern anterior spinal fixation options include interbody spacers, intervertebral spacers, screw-plate fixation systems, and screw-rod fixation systems. ALIF has been reported to be mechanically unstable when iliac bone graft alone is utilized without supplemental spinal fixation (Humphries et al 1961).

In an attempt to improve the success rate of interbody fusion and possibly eliminate the need for adjunctive posterior fixation, a variety of interbody spacers have been introduced. These include allograft femoral rings, cylindrical fusion cages such as the BAK device, Moss titanium fusion cages, as well as carbon fiber anterior fusion devices. This is a rapidly emerging field and many of these devices have shown great promise in early studies.

When an entire vertebral body requires replacement, options include autograft, structural allograft, fusion cages, and polymethylmethacrylate (PMMA). Such constructs are generally used with supplemental spinal fixation either anteriorly, posteriorly, or in a combined anterior–posterior fixation construct.

Anterior fixation options include both screw-plate and screw-rod devices. Anterior screw-plate devices (e.g. Synthes locking plate, Z-plate, and the CASP system) permit in situ spinal fixation. Anterior screw-rod devices (e.g. Kostuik-Harrington, anterior TSRH, and Kaneda) are more versatile and permit both distraction and compression as well as deformity correction, and can be more easily adapted to fixation over multiple levels than screw-plate systems. Placement of bulky fixation devices across the L5–S1 junction is generally discouraged owing to the proximity of vascular structures to the implant device.

Implant materials

The chief implant materials used in spinal surgery are stainless steel and titanium alloys. They provide strength, can be contoured to match bony surfaces, and are biocompatible. Stainless steels are alloys composed mainly of iron (>58%), chromium (17–20%), and nickel (13–16%). As a class of alloys, they are favored owing to the inexpensive nature of their base elements as well as the wide range of structural and mechanical properties that can be achieved by varying the constituent ratios. Pure titanium is a good material for orthopedic use due to its low density, high ductility, and MRI/CT scan compatibility. Its chief drawback, however, is its low modulus of elasticity. As a result, titanium is usually combined with aluminum and vanadium to produce the alloy Ti-6Al-4V, which has a greater tensile and fatigue strength than stainless steel. Although the modulus of elasticity of this alloy is greater than that of pure titanium, it is still less than the modulus of stainless steel. As a consequence, larger hardware must be used to provide comparable rigidity if titanium is used. The structural properties of titanium alloys are approximately half those of stainless steel alloys (Metals Handbook 1975).

PMMA is sometimes used as an adjunct to internal fixation. PMMA is stiffer than cancellous bone, but less stiff than cortical bone. It is used primarily in cases where bone quality compromises fixation. Several authors have demonstrated the efficacy of PMMA in enhancing screw fixation.

SPECIAL PROBLEMS

Spinal decompensation

Normal spinal balance exists when the head is centered over a level pelvis and shoulders in the coronal and sagittal planes. In the sagittal plane, the normal lordosis of the lumbar spine permits the head to be balanced over the pelvis with the hips in full extension (Lenke et al 1994). Spinal decompensation is the result of any condition in the coronal and/or sagittal plane that alters this normal alignment. The effects of spinal decompensation on the patient are significant. Complaints associated with decompensation include apparent leg length discrepancy, gait abnormalities, back pain, spinal fatigue, decreased standing tolerance, pelvic obliquity, difficulty with sitting, cosmetic deformity, and degenerative changes in adjacent motion segments. The flat back syndrome is an example of spinal decompensation in the sagittal plane. This problem arises following a lumbar fusion that results in a loss of lumbar lordosis with subsequent forward inclination of the trunk and an inability to stand erect without hip or knee flexion. It is generally seen in the adult who has undergone surgical fusion extending below L3. In young patients in whom the sacrum is not part of the fusion, decompensation may occur at the last level of the mobile spine, with a corresponding acute hyperextension that can cause nerve root impingement. Further spinal reconstructive surgery to restore lumbar lordosis through osteotomy procedures is frequently required to treat this disabling condition.

Pediatric disorders

The unique aspects of the pediatric spine that must be taken into consideration are the potential for further growth, the difference in elasticity of ligaments compared with adults, the differences in osseous tissue (thicker, biologically more active periosteum), and the relatively smaller size of the spinal elements. Because pediatric bone has not yet achieved its peak bone mineral density and deforms at lower peak forces, it can absorb more energy to ultimate failure. Vertebral body and sacral growth characteristics may have direct consequences for the disease process, as in spondylolisthesis progression, or may affect treatment, as in the crankshaft phenomenon occurring following posterior fusion.

Revision surgery

Spinal revision surgery may be required to treat a variety of problems such as pseudarthrosis, coronal or sagittal decompensation, or deterioration of motion segments adjacent to a prior fusion. Extension of the fusion and pseudarthrosis repair, as well as osteotomies, may be indicated depending on the underlying problem. The reconstructive spinal surgeon must design internal fixation constructs that create a stable environment for fusion to occur in balanced alignment with adjacent spinal motion segments.

Osteoporosis

Metallic constructs implanted in osteoporotic bone cannot be expected to provide solid mechanical support. This situation poses a serious challenge in the treatment of osteoporotic patients. The number of osteopenic (mainly osteoporotic) patients has grown markedly in the USA and Europe, and the treatment of mechanical insufficiency in this population remains a great challenge. The weak purchase of screws in osteopenic bone precludes the application of forceful corrective maneuvers. It has been demonstrated that hook claws on the laminae may provide for a better grip than screws (Coe et al 1990). In other studies, cement or bone graft has been utilized to augment screw purchase in osteopenic vertebrae (Zindrick et al 1986).

SIJ fusion

The nature and significance of movement in the SIJ as well as the relationship of the SIJ to lumbar pain symptomatology remain controversial. Overlapping innervation and referred pain phenomena make the diagnosis of pain emerging from the SIJ difficult. The basic role of the SIJ is to absorb, with minimal movement, the loads of the axial skeleton. All biomechanical loads, whether they are due to sitting, standing, or walking, must pass through the SIJ. Surgical fusions for SI dysfunction are rarely performed except for SI dysfunction following a major traumatic injury. However, recent studies have demonstrated painful incompetence of the SIJ by radiographically controlled injections, and surgical arthrodesis of the SIJ has been reported to provide satisfactory pain relief in select cases. Another related area of ongoing investigation is the consequence of fusion of the spine to the sacrum in relation to SI function and SI pain symptomatology.

CONCLUSIONS

1. Although spinal arthrodesis is widely practiced and is constantly being perfected, it should be appreciated that fusion is a crude solution to the malfunction of sophisticated anatomic mechanisms that occur in nature.

2. While restoration of function of the patient can be accomplished by eliminating motion at the affected level, restoration of normal function of a pathological motion segment is not possible utilizing present technology. Future approaches may abandon fusion altogether and seek other means of treating painful deformity or instability.

3. Restoration of motion is the objective of reconstructive surgery in other areas of orthopedic surgery.

4. Artificial discs and artificial ligaments may become the state of the art in futuristic orthopedics in the lumbosacral junction in the next century.

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