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CURRENT CONCEPTS IN SPINAL FUSION / REVIEW ARTICLE

History of Spinal Fusion: Where We Came from and Where We Are Going

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Abstract Spinal fusion surgery is performed all over the world to help patients with cervical and thoracolumbar pathology. As outcomes continue to improve in patients with spine-related pathology, it is important to understand how we got to modern day spinal fusion surgery. Scientific innovations have ranged from the first spinal fusions performed with basic instrumentation in the late nineteenth century to contemporary tools such as pedicle screws, bone grafts, and interbody devices. This article tracks this technological growth so that surgeons may better serve their patients in treating spine-related pain and disability.

Keywords history of spinal surgery · spinal fusion · bone graft · spine technology

Introduction

The severity of spinal disease physicians faced in the late nineteenth century can hardly be overstated: traumatic injuries, congenital defects, and tuberculosis or Pott's disease often resulted in severe neurologic impairment and global disability [47, 88]. With the advancements in antiseptic surgery by Joseph Lister and others and innovations in anesthesia by William T.G. Morton, bold surgeons dared to help patients suffering from spinal deformity [57, 79, 98].

In the 1890s, W.T. Wilkins described treating a newborn with spina bifida. Upon dissection, he found that "the last dorsal and the first lumbar vertebra were . . . separated by a half-inch and a hernia protruded through the fissure . . . . The hernia was reduced and the two vertebrae were held together by a figure-of-8 carbolized silk ligature" [11, 38]. An American surgeon, Berthold Earnest Hadra, attempted to treat a patient with progressive neurologic decline from a fracture dislocation of the cervical spine. In 1891, he described using a wire to bring together the sixth and seventh cervical vertebrae for stability [38, 47]. In the early twentieth century, two giants in spine surgery, Russell Hibbs and Fred Albee, pushed the boundaries of science to treat patients suffering from Pott's disease. Hibbs's original technique involved treating a 9-year-old boy with a kyphotic deformity by removing the spinous processes and laying them down over the interspinous space to promote fusion and repairing the periosteum over the fusion mass [85]. In this period, Albee, citing his experimental works on dogs, proposed using bone grafting to enhance spinal fusion in patients suffering from Pott's disease [53].

In modern times, pedicle screws, interbody devices, and osteoinductive and osteoconductive bone grafts all work to assist in forming a solid fusion mass. Techniques in spinal fusion have advanced exponentially over the past 25 to 50 years, as has understanding of the biology and biomechanics surrounding spinal fusion. As we reflect on this history, we must also look forward to how spinal fusion will change over the next 50 years. In this article, we delve into the history of specific aspects of spinal fusion, such as instrumentation and bone grafts, and how scientific innovations are improving the outcomes of spinal surgery.

Fusion Without Instrumentation

The Hibbs technique of laying down bone graft over a fusion bed can be considered an early example of fusion without instrumentation. This technique was modified and further popularized by Melvin Watkins in a classic 1953 article outlining a posterolateral incision to lay down bone graft between transverse processes [96]. Thompson et al. described a similar technique to create a trough between

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transverse processes to lay down "match stick" bone grafts [87]. This method of spinal fusion is still a viable option for surgeons attempting minimally invasive lumbar fusion [37].

Spondylolisthesis at the lumbosacral junction was first described by Hermann Friedrich Kilian in 1854 and drove advances in anterior spinal fusion [15]. In 1932, Capener described treating patients with a bone dowel between L5 and the sacrum to help correct the forward slippage of the L5 vertebra [15]. Around this time, B.H. Burns performed an anterior lumbar interbody fusion in a 14-year-old boy with a traumatic spondylolisthesis, using a bone dowel from the patient's tibia to achieve fusion between L5 and the sacrum [13, 25]. Rather than accessing the intervertebral disc space anteriorly, in 1944, Milligan and Briggs described using a posterolateral approach to access the intervertebral disc space [9, 25]. A bone peg was placed in the intervertebral disc space to augment a developing fusion mass in what can be described as a precursor to modern posterolateral interbody fusion (PLIF). Modifications in PLIF techniques have since been adopted for this technically demanding procedure [21, 56].

Instrumentation for Enhancing Fusion

The development of instrumentation to supplement fusion began with the steel wires used by Hadra in 1891 to supplement his posterior cervical surgery. Wire constructs were used in a similar pattern by Fritz Lange of Munich, Germany, to help treat patients with scoliosis [53]. The area of spinal instrumentation, however, has seen tremendous innovation for the purpose of supplementing biomechanical strength while the spine fuses. This includes screws, plates, cages, and interbody devices designed to enhance stability.

Harrington Rods

Between the 1940s and 1960s, there were innovations in facet screws and the use of vitallium in spinal surgery, but the most impactful instrumentation developed during this period was the Harrington rod, in 1962 [25, 49, 91]. Paul Harrington was able to correct scoliosis by first using a concave-distraction technique with a rod and hooks [32, 40, 41]. This rigid support augmented the creation of a spinal fusion but also led to a flattened spine in the sagittal and coronal planes [1, 41]. Nevertheless, Harrington rods were associated with excellent post-operative satisfaction scores after 20 years' follow-up [62].

Pedicle Screws

Surgeons treating lumbosacral spondylolisthesis, scoliosis, and other conditions of the spine realized early on that post-operative immobilization led to high rates of pseudarthrosis. Developments such as facet screws seemed to improve fusion rates, but early innovators of spinal instrumentation, such as H.H. Boucher, recognized the potential strength of interpedicular fixation [7, 45, 86]. Raymond Roy-Camille was the first, in the early 1970s, to describe using screws oriented sagittally through the facet/pedicle [25, 45, 75, 76]. This three-column fixation strategy is still widely used today [54]. Further innovations to pedicle screw instrumentation have included the polyaxial screw, fenestration, and variations in screw pitch in order to provide more robust fixation in spinal fusion [31, 34, 61].

Given the stable fixation of these screws within the pedicle and vertebral body, there have been several innovations in connecting screws placed at varying levels within the spine. Roy-Camille first used specially designed cobalt–chromium alloy plates to connect pedicle screws for lumbosacral fusions in the 1970s [45]. In the 1980s, Friedrich Magerl used external spinal fixation with pedicle screws for unstable spinal injuries [60]. Arthur Steffee developed titanium plates with specially designed screw slots for implantation in the lumbosacral spine in the late 1980s [101]. These developments, along with the polyaxial screw, helped pave the way for the screw–rod constructs in use today.

Interbody Devices

Research on intervertebral cages for spinal fusion was based on attempts to achieve spinal fusion in horses with wobbler syndrome in the 1970s [25, 99] by decompressing the spinal cord and thereby creating a solid cervical spinal fusion [93]. In order to strengthen this fusion biomechanically, a specially designed cylindrical basket was placed between the vertebrae [4], a method that was subsequently modified by Stephen Kuslich for use in humans [51]. The Bagby and Kuslich or "BAK" cage was used for an ALIF and had a 91% fusion rate at 2 years post-surgery.

PLIF, lateral lumbar interbody fusion (LLIF), and transforaminal lumbar interbody fusion (TLIF), all widely used interbody surgeries, allow for three-column support of a lumbar fusion [65]. Ralph Cloward's first description of PLIF involved placing autograft/allograft in the intervertebral disc space [21]. During the 1980s and 1990s, Harms et al. were able to pioneer a TLIF approach that used bone graft packed in a titanium cage [39]. By the late 1990s, polyetheretherketone (PEEK) cages offered an inert, rigid material that had a Young's modulus similar to that of cortical bone and could be used in the intervertebral disc space [97]. Since then, there has been tremendous growth in PEEK device technology in ALIF, TLIF, and PLIF applications [67, 68, 77]. It is important to note, however, that unlike the titanium used for specially designed cages, PEEK is hydrophobic, which can inhibit bone growth [63]. Advances in surface technology continue to address this issue of osseous integration of cage material. LLIF has also gained in popularity in the past decade as a minimally invasive technique to place a large bone graft in the intervertebral space [52, 78]. With this technique, however, surgeons should be cognizant of the temporary but common occurrence of groin pain or numbness.

Cervical Spine Instrumentation

Fusion in the cervical spine using an anterior approach was first described by Robert Robinson and George Smith in the 1950s [27, 74]. By removing disc material and osteophytes and fusing a segment of the cervical spine, they treated cervical spondylosis through an anterior cervical discectomy and fusion (ACDF). Cloward modified this anterior spinal

fusion technique using a bone dowel to supplement fusion [22]. A technique to treat multilevel disease pioneered by Boni et al. used a modification of the Cloward technique [6]. This involved decompressing the spinal cord anteriorly with a corpectomy and then inserting an autologous graft into a prepared trench.

Numerous plate–screw constructs have been designed to augment anterior cervical surgery [5, 17, 18, 66]. A recent meta-analysis showed that the use of an anterior plate with screws is associated with better fusion rates and decreased subsidence [69]. Recent innovations in anterior cervical plates include the use of locking screws and variable-angle screws to augment fixation strength [66, 71]. There has also been significant growth in the use of stand-alone cages for ACDF, on the theory that these lower-profile devices reduce the chances of implant-related complications such as dysphagia while providing an adequate fusion bed within the cervical spine [46, 55].

Significant research and iterative innovations in posterior cervical instrumentation, from wire constructs and plates to the lateral mass screw–rod constructs in use today, have resulted from the struggles to treat patients with severe rheumatologic deformities [20, 23, 70, 72].

Bone Grafts

Bone grafts have been used to treat dental and orthopedic injuries since ancient times. Mayans used jadeite, gold, and turquoise for dental inlays, and ancient Romans used gold for dental implants [28, 33, 84]. The first known use of an autograft was in Germany in 1821, whereas the first use of an allograft was for a humeral defect in a 4-year-old boy in 1879 by Sir William Macewen [48, 59]. During spinal surgery, bone grafting plays a vital role in promoting bone healing. Grafting materials can be categorized as osteoinductive, osteoconductive, osteogenic, or some combination of these properties. The history of bone grafting is complex, but it provides valuable insights into how new developments in bone graft technology can augment fusion.

Autografting is the gold standard in bone grafting because it can work as an osteoconductive, osteoinductive, and osteogenic material for bone healing. Hibbs's early example of an autograft [42] involved the use of a material through which bone could grow (osteoconductive), providing factors encouraging bone growth (osteoinductive), and cells producing bone itself (osteogenic).

Iliac crest bone grafting was used as early as 1921, when it was employed for the treatment of a fractured mandible [19]. It has strong structural and biological properties and has been used extensively in spinal surgery to augment a fusion mass [58, 81]. Iliac crest bone graft harvesting, however, is associated with a high rate of complications, including infection and pain [2, 80].

Allografting provides an osteoconductive environment for bone growth in spinal fusion. One of the first uses of an allograft in spine surgery was in anterior cervical fusion in 1976 [10]. Advantages of allografting include the avoidance of morbidity associated with autograft harvesting from the iliac crest; plus, a large quantity can be used during spinal surgery, which is especially important during multilevel fusion [29]. Disadvantages of allografting include a lack of vascularization and limited osteoinductive or osteogenic properties [83].

Demineralized bone matrix (DBM) provides both osteoconductive and osteoinductive properties as a bone graft material [48]. The original work surrounding DBM was based on Marshall Urist's original research on the "morphogenetic" properties of decalcified bone matrix [90]. Subsequent work showed promising results in bony defects in a rat femoral diaphyseal pre-clinical model [30]. DBM has been modified and is now frequently used in the augmentation of spinal fusions [43]. Although it offers an osteoinductive and osteoconductive bone graft substitute, disadvantages include batch-to-batch variations in DBM products [3].

The most widely used osteoinductive material is bone morphogenetic protein (BMP). Once again, it was the pioneering work of Urist that showed the potential for BMP to encourage and enhance bone growth [89]. Original pre-clinical research using recombinant human BMP-2 (RhBMP-2) and RhBMP-7 showed promising results in terms of augmenting spinal fusions [50, 100]. Although the rise in the use of RhBMP-2 in particular has sparked controversy regarding high rates of complications and off-label uses, there is evidence supporting its use in appropriate clinical situations [16, 82].

New Developments in Spinal Fusion: Where We May Be Heading

Innovation is in progress worldwide for the purpose of enhancing the strength of spinal fusions. Furthermore, the need for patient-specific treatment plans has pushed scientists to create new instrumentation, novel bone grafts, and translational medical research for spinal fusion. Surgeons continue to work toward creating a fusion mass using the most minimally invasive techniques possible.

As such innovations make it easier for surgeons to create a fusion mass in the spine, there has been significant interest and research in attenuating abrupt transitions between a mobile adjacent spinal level and a fused rigid spinal segment using tethers [12]. These tethering technologies likely will play an important role in the treatment of adult spinal deformity to prevent the complex problem of proximal junctional kyphosis, given the long segment fusions often used to correct sagittal plane deformity. We look forward to future research in this area to describe the optimal techniques in order reduce the risk of adjacent segment disease after a solid spinal arthrodesis.

The design of RhBMP-2 and RhBMP-7 products made use of basic science research in developing recombinant human proteins and the biology of osteocyte differentiation. Similarly, surgeons are using advancements in nanotechnology to design robust interbody devices with advanced surface technology to encourage bone growth [92]. Cao et al. have designed bioabsorbable cervical fusion cages that allow for bone growth while slowly being reabsorbed by the body [14]. Roughening the surface of titanium using

nanotechnology within interbody cages has also shown encouraging results in enhancing osteocyte differentiation toward an osteogenic lineage [26, 36].

Carriers for osteoinductive proteins have been extensively studied to enhance safer and more powerful drug delivery at the site of spinal fusion. Specifically, the carrier for RhBMP-2 has typically been the absorbable collagen sponge. There is exciting new research on the delivery of RhBMP-2, in terms of timing and location, to best enhance spinal fusion. Hsu et al. have examined the use of a peptide amphiphile in order to improve BMP-2 delivery at the time of surgery and potentially reduce the dose of BMP-2 required for fusion [44]. Another study looked specifically at a polyelectrolyte complex for use as a BMP-2 carrier, noting improved and more controlled bone growth [94]. Scaffold material has also been highly engineered to induce local BMP-2 [8, 95]. Bouyer et al. were able to coat a poly(lactic-co-glycolic acid) tube to allow for tunable delivery of BMP-2 in rat femoral defect [8]. These innovations likely point to a future with varying methods to administer osteoinductive material at the fusion site.

Stem cells offer the potential to differentiate into bone-forming cell lineages that may have advantages for spinal fusions. In one rabbit study, a large dose of bone marrow stem cells mixed with hydroxyapatite performed better than a low dose of bone marrow stem cells mixed with hydroxyapatite, suggesting a role for stem cells to enhance fusion [64]. The use of stem cells in this manner needs further research, however, given mixed results regarding the vector for the study, the carrier for the stem cells, and the manner of delivery [24, 35]. Definitive pre-clinical and clinical studies showing benefit over traditional methods of providing osteoinductive material at the fusion site (i.e., autograft) are needed before the use of stem cells for spinal fusion is widely adopted [73].

In conclusion, there have been tremendous advances in spinal fusion since the first attempts at treating patients with Pott's disease in the late 1800s. Scientists and surgeons have worked to make use of developments in biology and biomechanics to design instrumentation that provides more reliable fixation and bone grafts with greater potential to promote fusion. There is certainly more to be done as our knowledge of stem cells, nanotechnology, osteoinduction, and osteobiologics develops.

Compliance with Ethical Standards

Conflicts of Interest: Sohrab Virk, MD, MBA, declares no conflicts of interest. Sheeraz Qureshi, MD, MBA, reports consulting fees from Stryker, Globus Medical, Inc., and Paradigm Spine; royalties from RTI, Globus Medical, Inc., and Stryker; ownership interest in Avaz Surgical and Vital 5; medical/scientific advisory board membership at Spinal Simplicity and Lifelink.com; board membership at Healthgrades and the Minimally Invasive Spine Study Group; and honoraria from AMOpportunities, outside the submitted work. Harvinder Sandhu, MD, reports personal fees from Biorestorative Therapies and Prosidyan Medical and stock or stock options from Amedica, Biorestorative Therapies, Paradigm Spine, Prosydian Medical, and Spinewave, outside the submitted work.

Required Author Forms Disclosure forms provided by the authors are available with the online version of this article.

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