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The Development of Minimally Invasive Spine Surgery

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Minimally invasive spinal surgery is one of the recent developments in the long history of our intellectual and technologic evolution in understanding and treating spinal disease. The earliest appreciations of spine pathology were found in Egyptian mummies dated 2900 BC and further elucidated in the Edwin Smith papyrus written circa 1550 BC. In fact, the first description of the spinal column was offered by the Egyptians in the *djet* symbol used for the god Osiris to represent stability, duration, and durability [1]. Hippocrates has been credited as the father of spine surgery, as evidenced by his seminal teachings and writings, underlined by his principles of sound reasoning and accurate observation [2]. The first concrete delineation of operative treatment of the spinal column was proposed by Paulus of Aegina in the seventh century, however [3]. He advocated and conducted direct removal of osseous tissue at the site of pathology. Since then, various approaches and techniques for operative treatment of the spine have been developed and evolved to address numerous conditions. In this article, we review the evolution of minimally invasive techniques in the spine. Although specific techniques applicable to the cervical, thoracic, or lumbar spine were often developed simultaneously and frequently were interdependent, a spinal "level" approach has been adopted in this article to enhance readability. Although this artificially imposes an apparent anatomic "logic" to the development of minimally invasive spinal surgery (which, in fact, did not exist), it does highlight the importance of specific innovations to our surgical techniques within each region.

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Cervical spine

Endoscopic-assisted transoral surgery

Fang and Ong [4] published a report on the first series of patients to undergo transoral decompression for irreducible atlantoaxial abnormalities in 1962. Undue morbidity and mortality led to limited acceptance of this approach, however. Subsequent advancements in imaging techniques and the availability of the operative microscope have significantly improved procedural safety and efficacy. Pathologic findings approached via this technique, however, may require extended exposures, including palatal resection, mandibular splitting, or maxillotomy, for decompression of clival abnormalities. These result in increased surgical time and complexity, prolonged recovery, and increased patient morbidity [5]. One of the disadvantages of using the microscope is that the lens is located at some distance from the working field, and in transoral surgery, the view is limited by the narrow dimensions of the oral cavity. Frempong-Boadu and colleagues [5] demonstrated the efficacy of endoscopic-assisted transoral surgery in limiting these extended approaches in a series of

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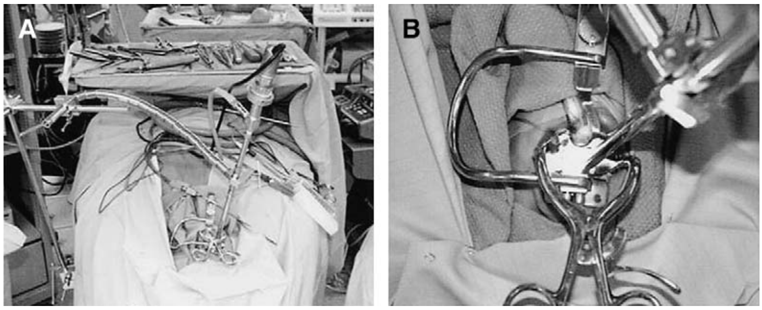

Fig. 1. Intraoperative photographs of an endoscope-assisted transoral procedure. The endoscope is rigidly affixed to the operating table via a flexible arm (*A*) and is introduced into the oropharynx to provide visualization and illumination (*B*). (*From* Frempong-Boadu AK, Faunce WA, Fessler RG. Endoscopically assisted transoral-transpharyngeal approach to the craniovertebral junction. Neurosurgery 2002;51(5 Suppl 2):S63; with permission.)

seven patients (Fig. 1). With the endoscope, the optics and illumination are within the surgical field immediately adjacent to the pathologic target. Thus, bypassing the limiting walls of the oral cavity, one can visualize even clival abnormalities without the extended exposures otherwise necessary [5].

Cervical microendoscopic laminectomy and discectomy

Scoville and Whitcomb [6] introduced the concept of posterior cervical disc surgery. Although the anterior approach to the cervical spine has become more popular, the posterior approach is an effective procedure in selected cases of laterally herniated disc fragments, isolated foraminal narrowing, multilevel foraminal narrowing without central stenosis, and continued root symptoms after anterior cervical discectomy and fusion as well as in cases in which anterior approaches are contraindicated. It is usually necessary to use moderately sized incisions and significant paraspinous muscle dissection in these operations, however. Postoperative wound pain and muscle spasms can therefore be significant, and postoperative recovery is often relatively slow.

The microendoscopic discectomy (MED) system (Fig. 2) was developed to minimize the tissue trauma and postoperative discomfort seen with open procedures (see section on lumbar MED). It provides equally good exposure of the involved segment compared with an open microdiscectomy. In cadaveric studies, Roh and coworkers [7] performed posterior cervical foraminotomies using the MED system or the conventional open technique. Their results demonstrated that nerve root decompression and the percentage of facet removed using the MED technique were equal to or greater than those achieved with the open technique. The transmuscular dilation with an endoscopic tubular working channel can minimize postsurgical pain and provide rapid postoperative recovery. Excellent results in early clinical series were reported by Adamson [8] and Fessler and Khoo [9]. Minimally invasive application of posterior cervical instrumentation was first described by Wang and colleagues [10] and remains in current development.

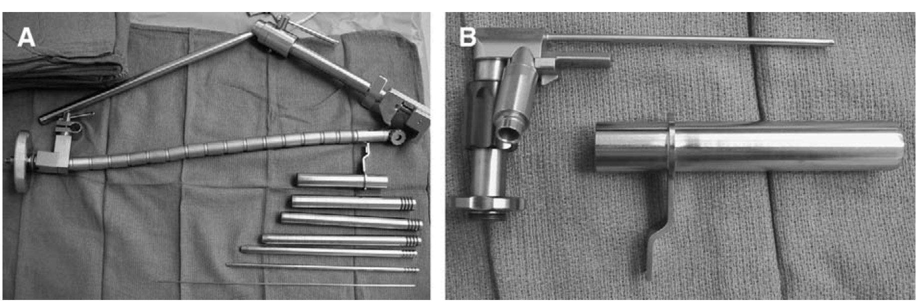

Fig. 2. (*A*) METRx MED (Medtronic Sofamor-Danek, Memphis, Tennessee) set with tubular dilators, tubular retractor, and table-mounted adaptor and flexible arm. (*B*) Endoscope and tubular retractor.

Thoracic spine

Thoracoscopic spine surgery

Jacobaeus [11], a professor of internal medicine in Stockholm, Sweden, is credited with performing the first thoracoscopic procedure in 1910. As an internist, he was involved in the diagnosis and treatment of pulmonary tuberculosis, and he thought that the ability to observe the pleural space was crucial. After his initial diagnostic procedure, Jacobaeus [12] described the technique of lysis of tuberculous pleural adhesions, which was performed with a cystoscope and a heated platinum loop. In 1990, with the introduction of videoimaging to standard endoscopy, the modern era of thoracoscopy began. Mack and coworkers [13] in the United States and Rosenthal and colleagues [14] in Europe first reported the technique of video-assisted thoracoscopic surgery (VATS) in 1993 and 1994. Thoracoscopic spine procedures were initially implemented for disc herniations, sympathectomies, pathologic conditions of the vertebral body, abscess drainage, and tumor biopsies. In the ensuing years, they have been implemented for scoliosis correction, anterior interbody fusion, osteotomies and bone grafting, corpectomies, and vertebral instrumentation in the treatment of tumors and fractures.

Posterior and posterolateral endoscopic discectomy

In a further attempt to reduce tissue trauma and enhance postoperative outcome, a thoracic MED approach has been developed to treat thoracic disc herniations from a direct posterior or posterolateral endoscopic approach. Jho [15] described the technique of endoscopic transpedicular thoracic discectomy with 0° and 70° 4-mm endoscopes, requiring relatively small 1.5- to 2-cm incisions and minimal tissue dissection. This approach avoids the need for separate skin incisions in the chest wall (required for thorascopic approaches) and the need for postoperative chest drainage. Chiu and Clifford [16] demonstrated the safety and efficacy of posterolateral endoscopic thoracic discectomy followed by application of a low-energy nonablative laser for shrinkage and tightening of the disc (laser thermodiscoplasty) using a 4-mm 0° endoscope. Thoracic discectomy using the METRx system (Medtronic Sofamor-Danek, Memphis, Tennessee) has been described by Isaacs and coworkers [17] in cadavers and clinically by Perez-Cruet and colleagues [18]. More recently, thoracic corpectomy and reconstruction using a minimally invasive technique has also been developed in cadavers and used clinically for trauma and tumor (see the article by O'Toole and colleagues elsewhere in this issue). Recently, minimally invasive techniques have also been used to remove intradural extramedullary tumors at all levels of the spine [19].

Lumbar spine

Chemonucleolysis

In 1941, Jansen and Balls [20] first isolated chymopapain, a proteolytic enzyme extracted from papaya latex. In 1956, Thomas [21] administered intravenous injections of crude papain to rabbits and noticed that their ears drooped. Intrigued by Thomas' article, Lyman Smith postulated the therapeutic use of papain to treat chondroblastic tumors. In 1963, Smith and coworkers [22] were the first to inject chymopapain into a herniated nucleus pulposus for the treatment of sciatica. This process, aptly called chemonucleolysis, alters the characteristics of the nucleus pulposus by liberation of chondroitin sulfate and keratin sulfate through hydrolysis of noncollagenous mucopolysaccharide proteins, leading ultimately to polymerization of the nucleus pulposus. Nordby and Javid [23] published the results of a 14-year study of 3000 patients treated with chemonucleolysis, with an 82% success rate for the first 1000 patients and an overall success rate of 87.2%.

Percutaneous arthroscopic discectomy

Ottolenghi [24] in Argentina in 1955 and Craig [25] in 1956 described posterolateral biopsy of the spine. In 1975, Hijikata and colleagues [26] demonstrated a percutaneous nucleotomy by using intradiscal arthroscopic techniques for disc removal in the treatment of posterior or posterolateral lumbar disc herniations under local anesthesia. After discography using Evans blue dye, specifically designed instruments were placed in a 5-mm cannula and inserted against the lateral anulus. A circular incision was made in the anulus, and the blue-stained nucleus pulposus was removed with pituitary forceps. Refinements to the technique involved the use of an automated system.

In 1983, Kambin and Gellman [27] performed a discectomy by inserting a Craig cannula and small forceps into the disc space after an open laminectomy to evacuate the nucleus pulposus and observed the effects on the surrounding anatomic features. In 1985, Onik and coworkers [28] reported the development of a 2-mm, blunt-tipped, suction-cutting probe for automated percutaneous discectomy at L4 to L5 or higher levels. Their reported outcomes indicate an overall success rate of 75%, with a complication rate of 1%.

Subsequent developments led to the design of a 2.7-mm glass arthroscope combined with a videodiscoscope with a single working portal [29]. This development enabled observation of periannular structures, including the foramen and the spinal nerve. Arthroscopic disc surgery allows removal of herniated discs via a posterolateral approach. This is accomplished with biportal access via triangulation into the intervertebral disc (Fig. 3) with in-line irrigation and suction [29].

Numerous studies on the efficacy of arthroscopic disc surgery have been published. Kambin and his colleagues [27,30] reported an 88% excellent or good outcome rate with arthroscopic microdiscectomy, and others have reported similar success. In a prospective randomized study evaluating the efficacy of microscopic disc surgery compared with endoscopic disc extraction, Mayer and Brock [31] achieved favorable outcomes with minimal complications using the percutaneous arthroscopic technique.

Percutaneous laser discectomy

Ascher and Heppner [32] were the first to use the technique of percutaneous laser discectomy to treat lumbar disc disease. Their technique involved measuring the intradiscal pressure before and after laser discectomy using a saline manometer. They postulated that the removal of even a small volume of tissue from the disc caused a corresponding decrease in intradiscal pressure [33].

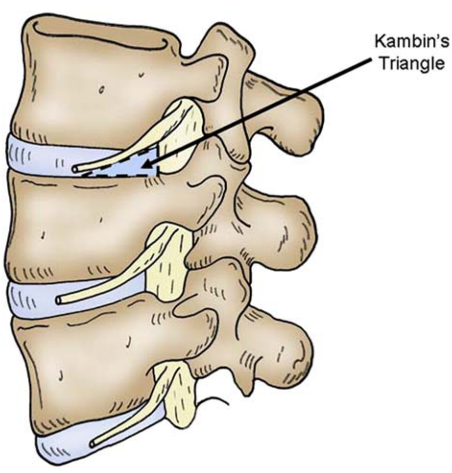

Fig. 3. Drawing of lateral lumbar spine depicting Kambin's triangular safe working zone for percutaneous arthroscopic discectomy. This zone is a right triangle in which one arm is the thecal sac, the other arm is the end plate of the caudal body, and the hypotenuse is the exiting nerve root.

The results of percutaneous laser disc decompression in cases involving back and leg pain with disc protrusions are still unclear. No controlled prospective studies have been performed to evaluate the results of percutaneous laser discectomy. The largest experience in the literature was reported by Choy et al [34]. They reported an 87.4% excellent result rate in a study of 333 patients, with a mean follow-up of 26 months. Early experience with the KTP/532 laser device was reported by Davis [35], who achieved an 85% success rate. Yeung [36] reported good to excellent results in 86.4% of cases with the KTP/532 device.

Percutaneous intradiscal radiofrequency thermocoagulation

Intradiscal electrical thermocoagulation (IDET) has been used to treat primary discogenic back pain. This therapeutic innovation is specifically designed to treat pain derived from internal disc disruption and annular tears. In 2000, Saal and Saal [37] reported on 62 patients with low back pain treated with IDET and showed that 71% of patients experienced a mean improvement of three points in their visual analog scale (VAS) back pain score.

Spinal endoscopy

In 1931, Burman [38] introduced the concept of myeloscopy for direct spinal cord observation. In 1934, Mixter and Barr [39] reported an open hemilaminectomy with intraoperative discotomy for treatment of intervertebral disc rupture into the spinal canal. In 1938, Pool [40] expanded on Burman's work and reported myeloscopic inspection of the dorsal nerve roots of the cauda equina. In 1942, Pool [41] introduced the concept of intrathecal endoscopy and reported the results of more than 400 myeloscopic procedures.

Myeloscopy fell out of favor for a time because of the morbidity associated with insertion of a large-bore scope into the dural cavity. The state of spinal endoscopy remained essentially the same until Ooi and colleagues [42] used an endoscope to examine the intrathecal space before surgery. Using improved technology, Ooi and colleagues [43] were able to describe pathologic features in greater detail, including chronic arachnoiditis and nerve root excursion during claudication, associated with lumbar spinal stenosis.

Lumbar microendoscopic discectomy

Microscopic lumbar disc resection through a tubular retractor was first reported by Faubert and Caspar [44]. Friedman [45] described a similar procedure using a large-bore chest tube. Using advances in endoscopic technology, MED through tubular retraction was first reported by Foley and Smith [46].

MED combines standard lumbar microsurgical techniques with endoscopy, enabling surgeons to address free-fragment disc herniations as well as lateral recess stenosis. The endoscopic approach allows smaller incisions and less tissue trauma compared with standard open microdiscectomy. Routine outpatient application reduces hospital stays and costs.

Muramatsu and coworkers [47] reported on a series of 70 patients who underwent MED and on 15 patients for whom Love's method was used to treat lumbar disc disease. MED resulted in less blood loss (mean of 12.1 mL) than Love's method (mean of 59.1 mL); analgesics (suppositories) were required by 52.0% of the MED-treated patients after surgery, whereas all the patients treated with Love's procedure required analgesics; and MED reduced the mean number of days before the patients became ambulatory (1.0 day for MED, 4.9 days for Love's method).

Guiot and colleagues [48] demonstrated the technical feasibility of percutaneous microendoscopic bilateral decompression of lumbar stenosis via a unilateral approach in a human cadaveric study, and successful clinical application of this technique has been reported by Khoo and Fessler [49]. The MED technique has also been applied in treating far lateral disc herniation [50], synovial cysts [51], and recurrent disc herniations [52].

Endoscopic pedicle screw fixation of lumbar spine

The video-assisted posterolateral approach was developed by Boden and coworkers [53]. Posterior keyhole approaches for endoscopic placement of pedicle screws have been performed using multiple portals or a single portal between the two pedicles.

Muller and colleagues [54] described the use of multiple portals in a cadaveric study to identify bony landmarks and to test the feasibility of performing endoscopic pedicle screw fixation. These investigators performed a transmuscular insertion of a pedicle screw-rod fixation device using a rigid operating sheath. The sheath (Thoracoport; Auto-Suture Company, Norwalk, Connecticut) measured 1.5 cm in diameter and 5 cm in length and was used with a disposable trocar system consisting of a blunt-tipped obturator, a threaded sleeve, and a shroud to secure the system. The surgical field was illuminated by an endoscope (Hopkins 11; Karl Storz GmbH & Company, Tuttlingen, Germany) with a diameter of 4 mm; a length of 18 cm; and angles of 0°, 30°, and 70°. The Diapason pedicle probe (Stryker Instruments, Kalamazoo, Michigan) with a blunt tip was used to discover whether the pedicle walls were intact. The system has pedicle screws that have a U-shaped screw head [54]. The connecting rods are fixed in the screw heads via a ball-ring interface and are locked with locking screws. The pedicle screws are placed using an inclinometer, which provides the surgeon with instant feedback during screw placement.

MacMillan and coworkers [55] described a fluoroscopically directed "arc"-based percutaneous transsacral fusion of L5 to S1, in which transgluteal dilators were used to reach the iliac wings adjacent to the ala. Drilling through the iliac wing at the ala then provided access to the L5-to-S1 disc and L5 vertebral body.

Percutaneous posterior fusion and instrumentation using a mechanically directed rod system was described by Foley and Gupta [56]. Minimally invasive transforaminal lumbar interbody fusion with percutaneous posterior instrumentation was described by Khoo and colleagues [57].

Laparoscopic lumbar spine surgery

The modern era of laparoscopy began in the 1980s when Kurt Semm performed the first appendectomy in Germany [58]. Semm, a physician and engineer, developed many tools that are still in use. The first human laparoscopic cholecystectomy was performed in 1987 by DuBois and colleagues [59]. With the advantages of laparoscopic exposure being championed by urologic, gynecologic, and general surgeons, it is natural that spine surgeons would consider extending these technologies to the anterior lumbar spine. The advantages of transperitoneal laparoscopic spinal surgery include improved observation of surgical anatomic features, marked reductions in postoperative pain, early hospital discharges, and reduced incidence of postoperative ileus. In

1991, Obenchain [60] reported the first use of a laparoscopic approach to the lumbar spine for a discectomy. Regan and coworkers [61] described the technique and reported preliminary results for laparoscopic anterior lumbar fusion.

Gaur [62] was the first to describe an endoscopic retroperitoneal approach for urologic procedures, which was later applied to fusion of the lumbar spine by McAfee and colleagues [63].

Additional minimally invasive developments

Application of image guidance systems in the spine

Image guidance systems are widely used in intracranial surgery and have been adapted to assist with screw placement since the mid-1990s. The use of image guidance systems for pedicle screw placement has improved overall accuracy. These systems typically rely on precise localization of the bony anatomy with preoperative CT. In this way, the transverse width, longitudinal depth, and trajectory angle can easily be measured on a computer-assisted work station.

Nolte and coworkers [64] described the principles of computer-assisted pedicle screw fixation. The overall accuracy of their system was 1.74 mm, using CT scans with 2-mm slice increments. Intraoperative surgical exposure of the posterior vertebral elements was performed using standard surgical techniques. An infrared camera (Optotrak; Northern Digital, Waterloo, Ontario, Canada) tracked specific instruments (ie, pedicle probe, awl, space pointer) equipped with light-emitting diodes. The dynamic reference was fixed to the spinous process of the vertebra to be instrumented. Normal bony landmarks and their correlations with the images confirmed the calibration accuracy. Using that computerized system, they reported a pedicle screw misplacement rate of 4.3% under clinical conditions.

Choi and colleagues [65] reported the use of computer-assisted fluoroscopic targeting for pedicle screw fixation. They described a system in which the pedicle entry site and the depth of insertion were determined by intraoperative anteroposterior and lateral fluoroscopic scans. Those authors compared the accuracy of placement with the fluoroscopy-guided system versus the CT-guided system and observed no significant differences.

Vertebroplasty

The spine is composed of a rich trabecular lattice of cancellous bone encased in a hard cortical shell. Moreover, the spine is exposed to degrees of compressive loads and tensile stresses that are in symbiotic biomechanical play with the inner and outer matrices of the vertebral bodies. Osteoporotic bone loss or neoplastic invasion of the vertebral bodies results in erosion of the cancellous network and development of vertebral compression fractures (VCFs), which can contribute to debilitating pain, neurologic deficit, gross spinal instability, and resultant deformity. Surgical management involves considerable risk because of the high prevalence of significant comorbidities in these patients. Surgical decompression and reconstruction involves internal fixation using screws, plates, wires, cages, or rods and requires extensive surgical exposure. The time required for recuperation from open fixation procedures can be lengthy. Obtaining satisfactory fixation in osteoporotic bone can be technically difficult, and the failure rate for spinal arthrodesis is significant.

In an attempt to reduce such invasive operative treatment, percutaneous vertebroplasty (PVP) was developed in 1984 by Galibert and Deramond [66] in France as a minimally invasive outpatient procedure to offer immediate pain relief by the injection of polymethylmethacrylate (PMMA) bone cement into the vertebral body through a transpedicular approach. Although rapidly popularized in Europe, PVP was not adopted in the United States until 1994 [67].

Kyphoplasty

In an effort to reduce the high incidence of cement extravasation and detrimental sequelae, such as infection, cement toxicity, and adjacent fracture development attributable to altered sagittal balance, kyphoplasty was developed in the mid-1990s by Reiley and his colleagues [68]. Kyphoplasty implements inflatable bone tamps inserted via a bilateral percutaneous transpedicular approach. Balloon inflation ultimately decreases intravertebral pressure by creating a cavity that is filled with PMMA and also distracts the vertebral end plates to restore vertebral height [69].

Summary

Minimally invasive spine surgery has evolved rapidly over the past decade. Nevertheless, its basis lies in ideas and techniques that date back much longer than that, nearly 100 years in some cases. Recent advances in areas like optics, miniaturizations, arc-based guides (Sextant; Medtronic Sofamor-Danek), fluoroscopic visualization, and image guidance have provided the technology necessary to enable rapid creation and evolution of surgical techniques. Fluoroscopy and the isolation of chymopapain first enabled the approach to the lumbar disc through minimal incisions and percutaneous passage through the spinal musculature. The inability to visualize the operative field directly and early complications from the enzyme limited widespread use of this procedure, however. Improvements in endoscopic optic technologies then enabled more direct manipulation of the disc. Nevertheless, small uniportal access limited visual acuity and the working size of instruments.

Simultaneously, however, these improved endoscopic optics were applied to "thoracoscopic" and "laparoscopic" spinal techniques. Combined with modifications of surgical instruments and anesthetic technique, it became obvious that much larger spinal surgical procedures could be performed through minimally invasive techniques than had previously been imagined. The technical difficulties of these procedures limited their widespread adoption, however.

Combining the "tubular dilator" approach with an endoscope (and later a microscope) switched the minimally invasive focus back to the posterior spine, and thus provided the technology needed to develop minimally invasive techniques rapidly for most spinal pathologic findings within a surgical field of view familiar to most spinal surgeons. The most common applications of these techniques are now being widely adopted. It is anticipated that with continued improvements in optics, image guidance, neuromonitoring, and biologic or genetic therapies, most spinal surgery may ultimately be performed using a minimally invasive technique.

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