1.3 The four pillars of minimally invasive spine surgery

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1 Introduction

The first ten years of the 21st century saw the use of minimally invasive surgical procedures become increasingly widespread. The goal of minimally or less invasive spine surgery (MISS) is to leave the smallest possible "surgical footprint" while still achieving a similar goal to that of open surgery, but with the same or an even better functional outcome for the patient. The key principles of MISS relate to the avoidance of injury to the surrounding tissues. These have been recently outlined by Kim [1], and may be summarized as follows: respect for the tendinous attachment of the major muscles involved (eg, the origin of the multifidus muscle at the spinous process in the lumbar spine); the utilization of neurovascular and muscle compartment anatomical planes for dissection; and the minimization of collateral soft-tissue injury through the use of modern, self-retaining, usually tubular retractors, which limit the width of the surgical corridor. These principles apply to all stages of the MISS procedure: the planning, the approach or access, the target surgery including a stabilization procedure if necessary, and finally, closure of the operative field.

MISS is not an "invention"; it is based on existing surgical principles, and developed out of the advances made in open surgical techniques and improvements in tools. There are at least four areas of orthopedic and neurological surgery that have been crucial to the development of MISS:

1. Microsurgical techniques have evolved considerably since the 1960s, with the increasingly widespread use of the microscope and also more recently of the endoscope for intraoperative magnification.
2. Percutaneous mini-open and more recent tubular access strategies have helped to minimize muscle injury.
3. With fewer landmarks and more limited visualization due to the smaller approach, imaging and navigation techniques have become indispensable for the accurate localization of the target pathology and the proper placement of spinal implants.
4. Finally, the refinement of MISS techniques has necessitated the development of specialized implants and guides for instrumentation of all the anatomical regions of the spine via anterior, posterior, and lateral approaches.

In this chapter, an attempt will be made to outline some of the basic developments that have taken place within these fields over recent decades, and which have made MISS possible. There are of course many areas that overlap or intersect. Several excellent reviews on these subjects have been published, and have been cited herein.

2 Spinal microsurgery using the microscope or endoscope

2.1 The microscope

The first practical use of the microscope in medicine probably dates back to the 17th century when Giuseppe Campani (1635–1735) invented an optical viewing system and reported in a letter to the pope in 1686 that he had used it successfully "for the examination of the wound of the leg" [2]. It was not until the early 20th century that otolaryngologists became the first surgeons to use the microscope. After World War II, ophthalmologists and vascular and plastic surgeons also began to make use of the microscope in the operating room, and added further technical improvements [3]. The introduction of the operating microscope into the field of neurosurgery and subsequently microneurosurgery is closely connected with Littmann from the company Carl Zeiss in Germany. In 1953, Carl Zeiss introduced the OPMI-1, the first true surgical microscope with a coaxial light system which allowed for adjustment of magnification without altering focal length (**Fig 1.3-1**).

The ear, nose, and throat surgeon House from Los Angeles introduced the Zeiss microscope into the United States after he had been trained in its use by ear, nose, and throat surgeons in Germany. The neurosurgeon Kurze from the University of Southern California was so impressed by the possibilities the new technique had to offer that he decided to spend some time in House's laboratory to gain experience in how it should be used. Kurze eventually performed the first neurosurgical operation using the operating microscope in 1957, when he removed a tumor from the seventh nerve in a five-year-old patient [4]. Soon after, in 1958, the neurosurgeon Donaghy [4] set up the world's first microsurgery research and training laboratory in Burlington, Vermont.

Around the same time, Malis from Mount Sinai Hospital in New York [5] introduced the bipolar coagulation technique into neurosurgery. The microscope rapidly became an indispensable tool in microsurgery. One of the landmark publications was the paper by the vascular surgeons Jacobson and Suarez [6], in which they demonstrated the contribution of the microscope in improving the outcome of small-vessel anastomoses. Jacobson was also the first to develop a two-person microscope that allowed a second surgeon to assist during the operative procedure [3].

In 1966, a Turkish neurosurgeon named Yasargil, who had trained in Zurich under Krayenbühl, spent time in Donaghy's laboratory to learn more about microsurgical techniques. Upon his return to Europe, Yasargil and his group made a large number of significant technical improvements to the operating microscope. Yasargil is, of course, best known for his pioneering contributions to cranial neurosurgery. However, he was also one of the first to introduce microsurgical techniques into spine surgery in the late 1960s and early 1970s. He and Caspar from Germany reported separately on their 5–7-year experience in lumbar microdiscectomy surgery using the operating microscope, but in the same journal and during the same year, in 1977 [7, 8]. Then a year later, Williams from Las Vegas [9] published a report on his clinical experience using a similar microsurgical approach for the treatment of lumbar disc herniations. He stated: "The microscope ... may revolutionize the quality of patient care for any practitioner of surgery. The instrument promotes far greater accuracy during surgical attack and provides the means for a more accurate clinical delineation between normal and pathological tissue."

Since these early experiences, the microscope has become an integral part of spine surgery. Spine surgery microscopes have been improved upon: while premium optics, illumination and focus remain basically unaltered, certain key improvements have been added (**Fig 1.3-2**). One of the main features of a spine surgery microscope is the depth of field, which frequently needs to be greater for spine surgery because of the type of instruments used. For example, the Leica M525 OH4, which was introduced in 2012, integrates a 400W Xenon bulb for better illumination and greater working distance for tubular spine surgery. Customized rotatable binoculars help the surgeon achieve a comfortable, ergonomic and physically well adapted body position during surgery. Current surgical microscopes include the option to integrate navigation technology and high-definition video documentation systems, as well as easy editing and transfer of videos to hand-held devices. Interactive control panels allow touch-screen control of microscope functions. Customized settings for individual surgeons can be stored and recalled at the touch of a button to ease workflow. At present, microscopy integrated with three-dimensional (3-D) navigation is used primarily for cranial neurosurgery, but also shows much promise for use in spinal procedures, especially once intraoperative CT scanners have become more available (**Fig 1.3-3**).

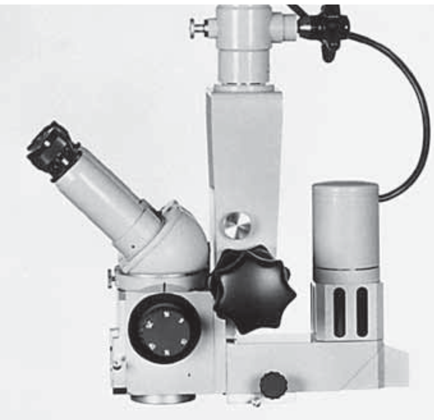


Fig 1.3-1 The Zeiss OPMI-1 was introduced in 1953, and was the first true surgical microscope with a coaxial light system in which the magnification could be changed without altering the focal length.

Fig 1.3-2 The Leica M525 OH4 provides 36% longer reach, height and clearance, allowing surgeons the flexibility required for microscope placement. (Image courtesy of Leica Microsystems Inc.)

2.2 The endoscope

A cystoscope (“myeloscope”) was used as early as 1938 for the evaluation of a disc pathology, nerve roots, and the cauda equina by Pool at Columbia University [10]. Much later on, in 1977, Apuzzo et al [11] were among the first to describe the use of an endoscope for spinal endoscopy. At this point, it should also be noted that percutaneous spinal discectomies or nucleotomies without direct visualization had been performed since the mid-1970s by Hijikata et al [12]. Hausmann and Forst [13] were the first to describe the insertion of a rigid arthroscope into the disc space to assist visualization during lumbar disc surgery. In 1986, Schreiber and Suezawa [14] combined the Hijikata technique with a percutaneously introduced endoscope for better visualization. Mayer and Brock [15] had used the endoscopic percutaneous technique for lumbar disc herniations from 1987 onwards, and in 1993 compared their results to those obtained with open lumbar microdiscectomy. Percutaneous endoscopic discectomy was performed using an endoscope angled at 70° coupled to a television and video unit, with the patient placed under local anesthesia. They found endoscopic discectomy to be an effective procedure for patients with “contained” and small subligamentous lumbar disc herniations.

More recent developments that have significantly contributed to the advancement of percutaneous spinal endoscopy include the introduction of various angled, high-resolution rod-lens operating endoscopes, variable-sized working channels, and highly specialized working instruments such as angled forceps, high-speed drills, and lasers (**Fig 1.3-4**). Using a number of these advanced techniques, in 2009 Ruetten et al [16, 17] reported excellent results on comparing percutaneous endoscopic surgery of the cervical and lumbar spine to open microdiscectomy. Percutaneous endoscopic spine surgery is currently gaining increasing acceptance among the surgical community, and it will be interesting to see whether the optical limitations of endoscopically-assisted surgery and the tools currently available will be as effective as microscope-assisted microsurgery for the treatment of spinal pathologies.

In 1997, Smith and Foley [18, 19] reported on a microendoscopic lumbar discectomy, in which endoscopes were used through tubular retractors to perform the discectomy. Excellent clinical results using this technique for the treatment of pathologies in the lumbar and cervical spine were subsequently reported [20–22].

However, several questions regarding tubular surgery remain, especially regarding the advantages of using the endoscope versus the microscope. In a personal interview with Kevin Foley, he stated that “the original tubular retractor surgeries were performed with small diameter tubes, typically 14 mm in diameter. Using an endoscope, rather than a microscope, allowed the surgeon to visualize off-axis anatomical structures, including anatomy that was adjacent to the edge of the tube but not directly beneath the long axis of the tube. This remains an advantage over a microscope, where an angled lens can be introduced into the surgical space and the surgeon can see ‘around the corner’. It allows the surgeon to work through a smaller approach

Fig 1.3-3 Photograph of the Brainsuite at BrainLab (Munich, Germany), showing display screens and state-of-the-art imaging equipment (MRI, CT scanner), permitting intelligent preoperative planning and intraoperative navigation.

Fig 1.3-4 Angled high-resolution rod-lens operating endoscopes for use in percutaneous spinal endoscopic procedures. The varied-angled Wolf endoscopes, with a large diameter of 4.1 mm and different-sized working channels, allow the use of highly specialized working instruments such as angled forceps, high-speed drills, and lasers. (Image courtesy of Richard Wolf Medical Instruments Corporation).

corridor. The disadvantages of the endoscope included: 1) lack of a 3-D image, 2) diminished image quality as compared to a modern microscope, and 3) ergonomic issues (eg, the need to move the endoscope to avoid 'fencing', or interference with surgical instruments introduced through the tube). Over the early years of surgery through tubular retractors, it became apparent that it was easier for most surgeons to learn to perform tube surgeries with a microscope, rather than an endoscope. When I lectured on this subject, I would teach that it was easier for a surgeon to learn one new skill, which I termed 'tubology' (the skillset needed to work through a small approach portal), rather than two new skills (tubology and endoscopy). Interestingly, surgeons that were already facile with endoscopy tended to prefer this over the use of the microscope with tube surgeries. This remains true in much of Japan, for example."

Most surgeons in North America currently use the microscope in preference to the endoscope when performing tubular surgery. This is probably due to the fact that the majority of surgeons are more familiar with the microscope, which is commonly used in cranial neurosurgery, and provides 3-D magnification.

Other fields of application for the endoscope have been explored. With the introduction into surgery of video imaging and further improvements in endoscopy, "video-assisted thoracoscopic endoscopy" was popularized in the early 1990s by Mack et al [23] and later by others. Video-assisted thoracoscopic endoscopy has been used with good clinical results for a range of spinal pathologies, using a variety of procedures including thoracic discectomy, corpectomy for tumor removal and the treatment of trauma, anterior release for deformity correction, and thoracic sympathectomy [24–28]. However, this technique is associated with a significant learning curve and is thus mainly performed in specialized centers. In 1991, Obenchain [29] was the first to report on the use of an endoscope for anterior lumbar discectomy; he termed this procedure "laparoscopic lumbar discectomy". Although in 1995 larger case series were reported in which patients were treated by laparoscopic lumbar spine surgery using the endoscope [30, 31], this technique has largely been abandoned in favor of the mini-anterior lumbar interbody fusion (mini-ALIF) approach due to the complex learning curve required, the increased risk of complications, and the high conversion rate to open surgery. However, computer-assisted endonasal endoscopic resection of odontoid pathologies to decompress the cervicomedullary junction has been described as a minimally invasive alternative to "maximally invasive" transoral surgery [32, 33].

3 Access strategies to the spine

3.1 Subperiosteal, intermuscular, and intramuscular approaches

Approaches to the spine can be divided into traditional subperiosteal approaches and muscle-sparing intermuscular or intramuscular approaches. The subperiosteal midline approach requires little knowledge of the muscular anatomy, and has been successfully used for many years for open decompression and fusion surgery in all anatomical regions of the posterior spine. However, this approach sacrifices large portions of the posterior stabilizing elements including ligaments, tendons, and bony structures. It may also lead to denervation and devascularization of the adjacent muscles. A partial exception to this is cervical laminoplasty, in which an attempt is made to reconstruct the posterior elements. The supraspinous and intraspinous ligament complex, the multifidus muscles of the lumbar spine, and the facet joints significantly contribute to the stability of the spine at their respective levels, and also serve as bridging structures to the adjacent levels. Disruption of these structures has been shown in animal and human anatomical specimen studies to cause significant instability, especially as regards flexion [34, 35]. In addition, subperiosteal muscle dissection and the use of self-retaining retractors may result in muscle atrophy [36–38], which in turn can lead to decreased force production capacity [39]. Mayer et al [40] evaluated trunk muscle strength in patients that had undergone lumbar surgery and found that in subjects that had undergone fusion procedures, it was significantly weaker than in those that had undergone discectomy. Muscle denervation due to extensive exposure, especially over the facet joint and pars interarticularis, is another source of muscle atrophy. All these factors have a significant impact on patient recovery and on the long-term effect of surgery both at the index level and as regards adjacent segments [41, 42]. This topic has been recently reviewed by Kim et al [1, 43]. Clinical results clearly support these observations; in a study comparing trunk muscle strength between patients that underwent open posterior versus percutaneous instrumentation, the latter was found to be associated with a 50% improvement in lumbar extension strength, whereas patients that underwent open surgery displayed no significant improvement in this respect [41]. Stevens et al [42] assessed the appearance of the multifidus muscle via MRI in patients treated by open versus MISS lumbar interbody fusion techniques, and found that for the open surgery group, marked intermuscular edema was observed on postsurgical MRI at 6 months postsurgery. In contrast, for patients in the MISS group, normal muscle appearance was observed on MRI.

Less invasive access and treatment strategies for the lumbar spine have been explored from the very beginning of spine surgery, and as previously noted, can be divided into muscle-sparing inter- and intramuscular approaches.

Intermuscular approaches make use of anatomically defined planes between muscle groups to access the spine [44]. In 1953, Watkins [45] was probably the first to describe a paraspinal approach between the fascial planes of the sacrospinalis and quadratus lumborum muscles to expose the transverse processes for posterolateral fusion. Wiltse [46] later reported on a modified transmuscular approach that differed from Watkins' exposure in that it involved a longitudinal separation of the sacrospinalis group between the multifidus and longissimus muscles, and not between the lateral border of the entire sacrospinalis group and the quadratus lumborum (**Fig 1.3-5**). Wiltse and Spencer [47] later described this approach for the removal of far lateral disc herniations, the insertion of pedicle screws, and decompression of the opposite side from inside the vertebral canal. Excellent anatomical reviews on this subject have also been published [44, 48].

This being said, it is interesting to note that one of the most popular, least invasive, and most widely used spinal procedures for anterior cervical discectomy uses an intermuscular approach, which was first popularized in 1958 by Smith and Robinson [49], and by Cloward [50] in the same year. An even less invasive approach was described in 1996 by Jho [51] for anterior cervical foraminotomy.

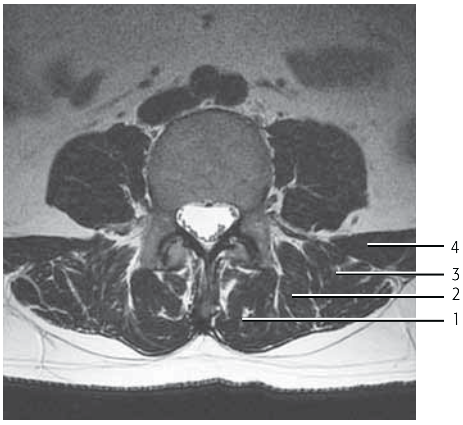


Fig 1.3-5 Axial MRI scan showing the lumbar cross-sectional anatomy including the intermuscular plane between the multifidus (1: medial) and the longissimus muscles (2: intermediate), and the plane between the longissimus (3: intermediate) and iliocostalis muscles (4: lateral).

In contrast, the intramuscular technique approaches the spine by splitting the muscles. Most percutaneous endoscopic and tubular retractor-assisted approaches are currently performed via this technique.

3.2 Percutaneous intra-/transmuscular approaches

For many, the age of MISS began when percutaneous chemonucleolysis was introduced in 1963 by Smith [52]. Smith injected chymopapain percutaneously into the disc of a sciatic patient to enzymatically dissolve the nucleus pulposus. However, this technique subsequently fell out of favor because the results did not seem to compare well with those for open surgery [53].

Percutaneous nucleotomy without direct visualization was then introduced in 1975 by Hijikata et al [12]. Modified techniques were subsequently described by the orthopedic surgeons, Kambin and Gellman [54], who added power shavers and other specialized instruments to the armamentarium of surgical tools. Their approach was based on the idea of decompressing the pressurized disc via an annulotomy from within, thereby preventing disc herniation, or reversing the disc herniation into the spinal canal. This approach was later termed the "inside-out technique" [55, 56]. In 1986, Schreiber and Suezawa [14] combined the Hijikata technique with the use of a percutaneously introduced endoscope for better visualization. In that same year, Kambin and Sampson [57] introduced the endoscopic transforaminal technique with posterolateral access (**Fig 1.3-6**). This endoscopic approach is based on accessing the disc space through Kambin's triangle in the "safe zone" between the exiting and traversing nerve roots (**Fig 1.3-7**), an area that is known to surgeons familiar with the open or MISS transforaminal lumbar interbody fusion (TLIF) technique [58]. Due to the limitations of this approach in accessing certain parts of the spinal canal, the full-endoscopic lateral trans-/extraforaminal approach was developed to provide adequate access to most of the spinal canal under continuous visualization [59]. The full-endoscopic interlaminar approach was subsequently added, which permits the treatment of pathologies that are outside the range of indications for the transforaminal procedure [60, 61]. Today, the recent technical advances enable the full-endoscopic procedure to be performed for the treatment of most disc pathologies and also for the decompression of lumbar spinal stenosis (**Fig 1.3-8**).

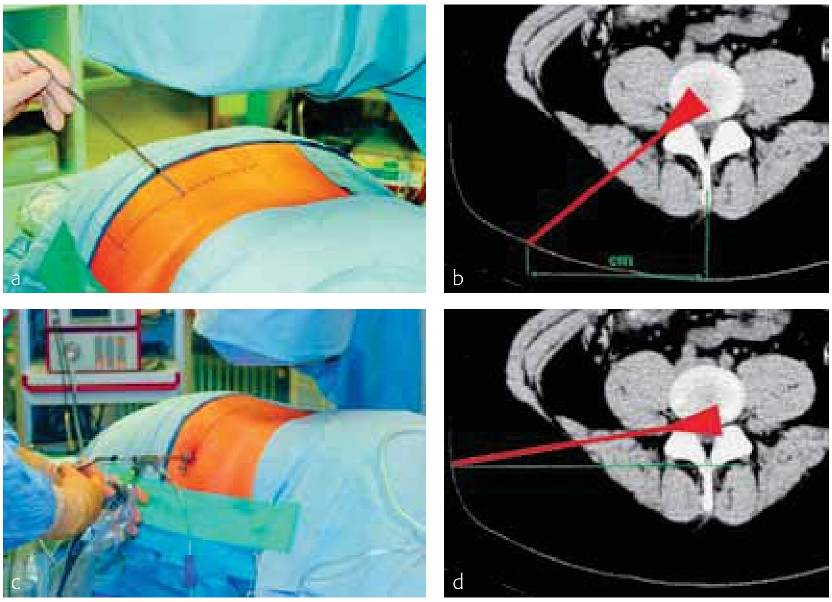


Fig 1.3-6a–d

a–b Endoscopic posterolateral approach. Skin entry point (**a**). View of the working area provided by this approach, which is mostly suitable for intradiscal pathologies (**b**).

c–d Endoscopic transforaminal approach. Skin entry point (**c**). This approach shifts the working area to the spinal canal (**d**).

(Images courtesy of Richard Wolf Medical Instruments Corporation.)

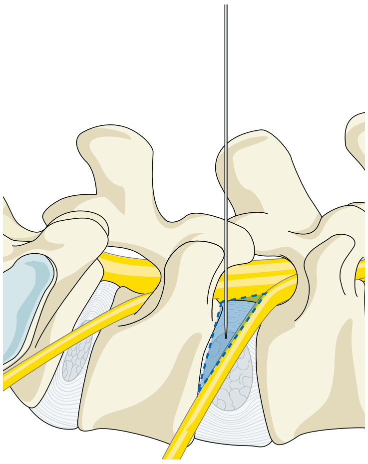


Fig 1.3-7 Endoscopic transforaminal technique using a posterolateral approach based on accessing the disc space through Kambin's triangle in the "safe zone" (dotted lines) between the exiting and traversing nerve roots.

Fig 1.3-8a–c

a Range of endoscopic instruments used for complex endoscopic procedures.

b Burrs and bone punches used for bone resection.

c Postoperative CT scan after interlaminar endoscopic approach for laminectomy showing good decompression. Arrows indicate lateral bone resection down to the floor.

(Images courtesy of Richard Wolf Medical Instruments Corporation.)

Of historical significance was the development of automated percutaneous lumbar discectomy in the 1980s. In this procedure, an outer cannula was introduced percutaneously against the disc space and a rotating inner cannula removed disc material under suction aspiration. Initial clinical results were reported in 1987 by Maroon and Onik [62], but the procedure eventually fell out of favor. Similarly, laser discectomy was first reported by Choy et al from Austria [63]. Mayer combined this technique with the endoscope for better visualization in 1992 [64]. However, both procedures have a very limited indication because they do not allow direct removal or decompression of pathologies within the spinal canal. The published literature has never fully supported their use, and laser discectomy is now rarely performed and cannot be recommended for the treatment of lumbar disc disease [65].

3.3 Tubular intra/transmuscular approaches

Other approaches have attempted to improve the microdiscectomy technique by using less invasive retractors. For example, surgeons have used various types of less invasive specular retractors for standard microdiscectomy cases following a typical subperiosteal dissection [66] (**Fig 1.3-9**). In 1997, Smith and Foley [18, 19] described microendoscopic discectomy (MED) for the treatment of lumbar spine pathologies, an approach that essentially consisted of a modification of the microtechnique in which an endoscope through tubular retractors was used to perform the discectomy (**Fig 1.3-10a**). These authors had worked on this approach in the laboratory since 1994, and the first clinical case was performed in early 1996 (according to a personal interview with Kevin Foley). This technique developed out of their experience gained with automated percutaneous lumbar discectomy and percutaneous endoscopic transforaminal approaches. Foley and Smith had been frustrated by their inability to adequately visualize the relevant anatomy and the pathology to be treated, by ergonomic issues related to small cannulae and tiny instruments, and by difficulty in adequately decompressing the nerve roots (Kevin Foley, personal interview). Microendoscopic discectomy was specifically designed to address these issues, while remaining a minimally invasive procedure that utilized a muscle-sparing, percutaneous approach. The METRx tubular retractor system was introduced in 2003, and allowed the use of the microscope during the operative procedure (**Fig 1.3-10b**). Excellent clinical results obtained with this technique for the treatment of pathologies affecting the lumbar and cervical spine were subsequently reported [20–22]. In North America, tubular access has gained widespread popularity, and is currently used to treat pathologies in all regions of the spine via posterior and lateral approaches. Access via tubular retractors allows complete decompression and instrumentation of the spinal segments, while preserving all the posterior stabilizing elements and protecting the muscle tissue and tendon attachments (**Fig 1.3-11**).

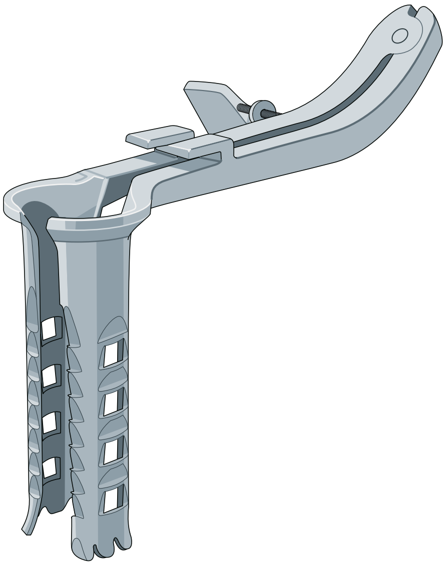


Fig 1.3-9 Caspar Micro Lumbar Retractor.

Tubular approaches have been used for the treatment of lumbar and cervical stenoses and disc herniations, lumbar foraminal narrowing, and synovial cysts. More complex procedures such as spinal fusion and deformity correction are also routinely performed through tubular retractors in conjunction with mini-open or percutaneous instrumentation techniques. Spine surgery through tubular retractors offers particular advantages when treating obese and/or geriatric patients [67–69].

There are several key observations to be made regarding tubular surgery, the first of them being the ability to achieve contralateral exposure and decompression of the lumbar spine via tubular retractors. The anatomical description and preliminary clinical results on unilateral laminotomy for contralateral decompression were first reported by Spetzger et al from Germany in 1997 [70, 71]. This procedure was subsequently improved upon with the introduction of tubular retractors, and now allows excellent decompression of the contralateral lateral recess and even lateral disc herniations and the contralateral foramen (**Fig 1.3-11**) [72, 73]. Synovial cysts can be resected safely, without compromising the facet joint, by approaching them from the contralateral side, ie, from the "normal" dura and anatomy

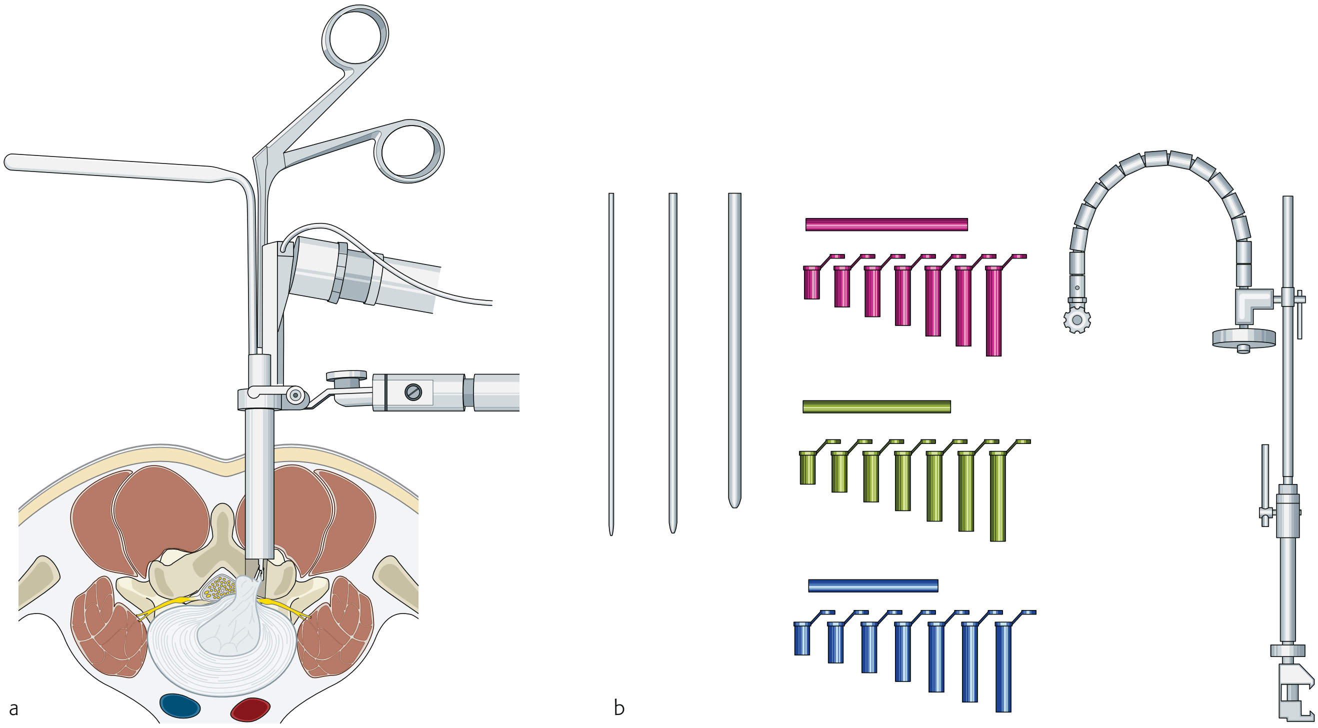


Fig 1.3-10a–b

a Illustration of endoscope-assisted disc removal with a pituitary rongeur through a tubular retractor based on Foley and Smith's initial description of this technique [18].

b The METRx system of sequential dilators. From left to right, the guide wire and two initial soft-tissue dilators (5.3 mm and 9.4 mm), tubular retractor sets with respective dilators (14, 16, and 18 mm), and flexible arm assembly with table attachment clamp (Medtronic-Sofamor Danek, Memphis, USA).

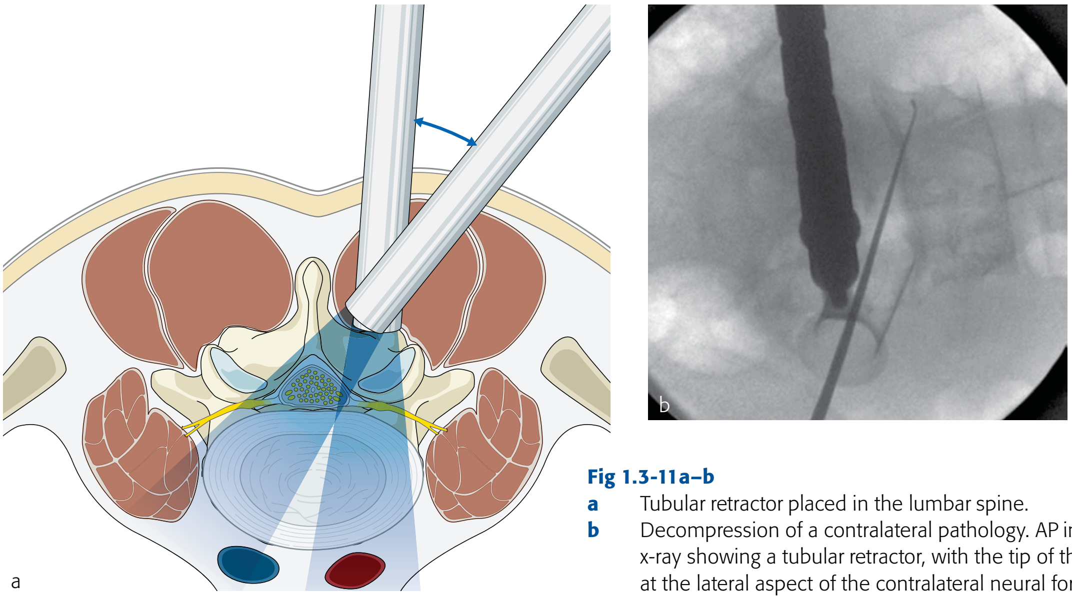


Fig 1.3-11a–b

a Tubular retractor placed in the lumbar spine.

b Decompression of a contralateral pathology. AP intraoperative x-ray showing a tubular retractor, with the tip of the nerve hook at the lateral aspect of the contralateral neural foramen.

(**Fig 1.3-12**) [74]. Tubular decompression appears to be especially useful for the treatment of lumbar spinal stenosis but is, however, associated with a significant learning curve [75, 76]. The clinical results are similar to those reported for open surgery. However, biomechanical and laboratory results indicate that laminectomy via tubular retractors or bilateral laminotomy cause less destabilization when compared to open bilateral laminectomy [77, 78]. Therefore the concept of decompressing patients with spinal stenosis and stable, grade 1 degenerative spondylolisthesis seems to be a reasonable one, and is currently under investigation. The results of a cost-utility study showed that tubular decompression without fusion for this category of patient is more cost-effective when compared to decompression and fusion [79]. The possibility of carrying out decompression of spinal structures without destabilization is considered to be one of the main advantages of tubular surgery. Critics of tubular surgery point out the learning curve and the possibly increased use of image intensification.

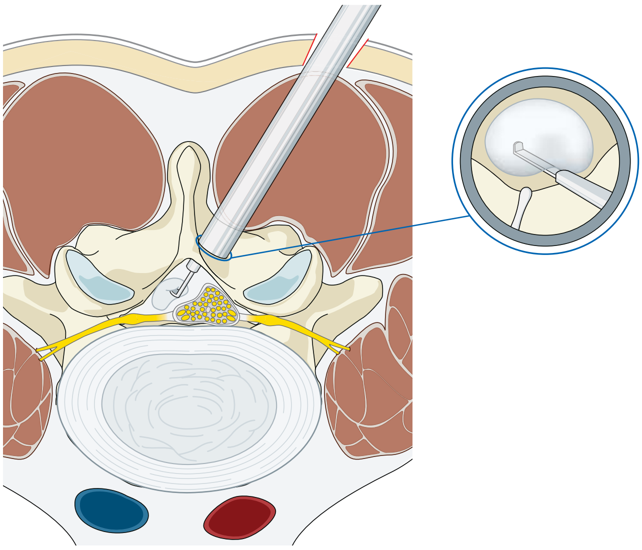


Fig 1.3-12 Diagram illustrating how spine pathologies can be resected safely and without compromising the facet joint by approaching them through a tubular retractor from the contralateral side, ie, from the "normal" dura and anatomy.

The first minimally invasive posterior lumbar interbody fusion was performed in early 2001 by Foley and colleagues (personal interview), and their preliminary clinical results were published in 2002 and 2003 [80, 81]. This was preceded by their description of percutaneous lumbar pedicle screw insertion using the Sextant system [82, 83]. Although minimally invasive posterior lumbar interbody fusion (PLIF) and TLIF surgery have become very popular over the years, the question remains whether the results are comparable to those obtained for open surgery. A meta-analysis comparing open to minimally invasive TLIF surgery found the fusion and complication rates to be very similar for both procedures [84]. On the basis of 16 studies (716 patients), the mean fusion rate for open TLIF was 90.9%, whereas for 8 studies (312 patients) the mean fusion rate for minimally invasive TLIF (mTLIF) was 94.8%. The complication rates amounted to 12.6% and 7.5% for open and mTLIF groups, respectively. Interestingly, the use of recombinant bone morphogenetic protein was higher in the mTLIF group (50% versus 12%).

Thoracic and upper lumbar pathologies requiring decompression and stabilization such as trauma, tumors, or infection are also targets for less invasive posterior intramuscular surgery. The feasibility and encouraging clinical results of an open posterior approach for thoracolumbar corpectomy with the implantation of expandable cages has been reported [85]. Similar results can also probably be achieved using less invasive tubular or expandable retractors [86, 87].

Tubular approaches are also routinely utilized for foraminotomy and laminectomy in the region of the cervical spine, and were first described by Adamson et al in 2001 [88] and Fessler and Khoo in 2002 [22] using the endoscope, then in 2007 by Holly et al and also by Hilton using the microscope through tubular retractors [22, 88–90]. Clinical reports have shown the results of microendoscopic foraminotomy with or without discectomy to be similar to those for traditional open procedures, with the duration of hospital stay and initial analgesic use favoring the tubular retractor approach, but no medium- or long-term differences have been observed [91–94].

The lateral approach to the lumbar spine using tubular retractors developed as a combination of traditional ALIF procedures, minimally invasive laparoscopic techniques, and MED. In 2006, Ozgur et al [95] reported on a mini-open technique for the treatment of pathologies affecting the mid-lumbar spine from a direct lateral transpsoas approach, utilizing electrophysiological monitoring to avoid nerve damage for the placement of structural interbody fusion cages.

This approach was based on the work of Luiz Pimenta from Brazil [96], who in 2001 had presented his preliminary results with this technique. The above-mentioned authors termed this approach "extreme lateral interbody fusion". Their technique, utilizing triggered electromyographic nerve monitoring and a table-mounted split-bladed retractor system, has become the standard procedure for lateral access to the mid-lumbar spine. It has gained increasing popularity over recent years, and provides excellent access not only to the lumbar spine but also to thoracic pathologies between levels T4 to L5. Although the initial results are very promising, the long-term results and the overall safety profile of this technique still need to be evaluated. The transpsoas approach reintroduced the concept of indirect decompression of the spinal canal, which had been previously observed in ALIF surgery [97]. Similar results were reported with lateral transpsoas interbody fusion [98], with a significant increase in dural sac dimensions, possibly due to stretching and unbuckling of the spinal ligaments, and a decrease in intervertebral disc bulging (**Fig 1.3-13**). Hence, one of the most important aspects of the lateral approach currently relates to interbody cage positioning and surgical objectives, ie, a more posterior placement for indirect decompression of the central canal and the foramen, or a more anterior placement for segmental sagittal correction.

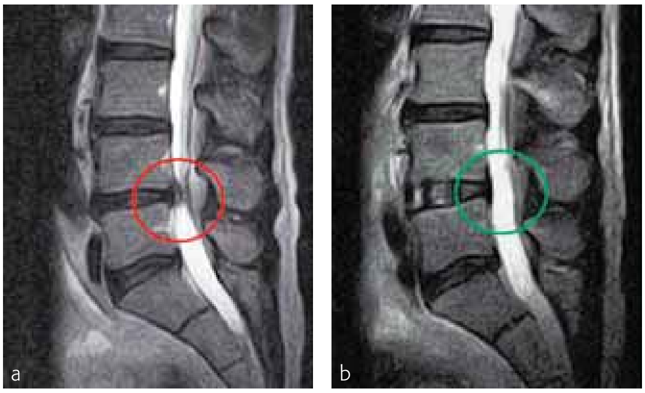


Fig 1.3-13a–b Indirect decompression of lumbar spinal stenosis via the extreme lateral approach. Sagittal lumbar MRI before (**a**) and after (**b**) implantation of interbody spacer.

A presacral approach to the lumbosacral spine without direct visualization has been developed and refined in recent years, and termed "axial lumbar interbody fusion" [99]. This approach was developed in light of the obvious risks and drawbacks connected with conventional anterior and posterior lumbosacral fusion surgery, such as injury to the lumbar muscles during the surgical approach, nerve root injury, risk of vascular or bowel injury, sympathetic dysfunction, blood loss, and deep vein thromboses. The possibility of reaching the L5/S1 and the L4/5 disc space through a paracoccygeal, transsacral approach avoids many of the aforementioned risks. At the same time, it allows discectomy with interbody fusion to be carried out, and sometimes also the restoration of disc and foraminal height without annular disruption. However, concerns regarding this approach include rectal perforation, infection at the incision site and/or along the access tract, connected with the implantation of the hardware, or of the disc space and adjacent vertebral bodies. Even though some clinical reports have shown promising results [100], other studies have found a higher failure rate [101], and the role of the presacral approach in MISS has not been clearly defined at this point.

Other approaches include "video-assisted thoracoscopic surgery" (VATS), which was popularized in the early 1990s by Mack et al [23] and later by others for various thoracic spinal pathologies.

In summary, all parts of the spine can now be accessed using minimally invasive muscle-splitting, intramuscular or intermuscular approaches, all of which have been examined in other chapters of this book. The majority of MISS procedures include percutaneous endoscopic and intramuscular tubular approaches to the cervical, thoracic, lumbar, and sacral spine. Many neurosurgeons and orthopedic spine surgeons currently use tubular or related access strategies. The main advantages of this type of surgery include the following:

- Less invasive access resulting in muscle and tendon sparing
- Ability to decompress spinal structures without destabilization
- Excellent contralateral exposure of the pathology in question
- Indirect decompression with implants, particularly with lateral approaches
- Reliance on interbody fusion rather than on posterolateral fusion.

4 Imaging, navigation and associated technologies

Imaging in spine surgery is essential for the accurate localization of the pathology to be treated, avoidance of wrong-level surgery, and the proper insertion of implants. This is even more important in the case of MISS procedures, which lack open visualization based on anatomical reference points that can be used as a basis for orientation and implant placement. Spine surgery inherently involves the potential of injury to the spinal cord, nerves, and vascular structures. Incorrectly positioned implants and screws that significantly breach the pedicle can cause spinal, nerve root, or vascular injury as well as dural tears and cerebrospinal fluid leakage. Intuitively, it makes sense that implants that have been placed with greater accuracy optimize the long-term outcome. There is general consensus among surgeons that imaging techniques are essential for the safe and accurate placement of spinal instrumentation regardless of the complexity of the operation, the anatomical region, the level of training of the individual surgeon, or the degree of operative comfort required. Traditionally, these imaging techniques have involved the use of x-ray or image intensifica-

Technique	**Indication**	**Pros**	**Cons**
X-ray	All spine surgery procedures	Inexpensive, universally available, technically easy to use	No 3-D information provided; requires postoperative CT scan to confirm implant positioning
Image intensification	All spinal instrumentation procedures	Real-time imaging	No 3-D information provided; radiation exposure to surgeon, staff, and patient; requires postoperative CT scan to confirm implant positioning
2-D stereotactic navigation or "virtual image intensification"	All spinal instrumentation procedures Replaces AP/lateral image intensification	Can facilitate workflow by eliminating the C-arm(s); less radiation exposure for the surgeon, staff, and patient	Significant cost involved; training of staff and x-ray technician necessary; learning curve required; changes affecting the anatomy over time are not detected (eg, stray K-wires or injection of vertebroplasty cement); requires postoperative CT scan to confirm implant positioning
3-D stereotactic navigation	All spinal instrumentation procedures	Can facilitate workflow by eliminating the C-arm(s); less radiation exposure for the surgeon and staff; improved accuracy of screw placement	Significant cost involved; training of staff and x-ray technician necessary; learning curve required; changes affecting the anatomy over time are not detected (eg, stray K-wires, vertebroplasty cement). Use of K-wires requires real-time image intensification
• **with intraoperative image intensifier-CT scan**		Image intensifier-CT can be brought in as needed, and can also be used for, eg, image intensification (K-wires), or intraoperatively to confirm spinal implant positioning	Limited image quality, especially in, eg, obese patients, cervicothoracic junction, etc; only 3–4 levels can be visualized in one "spin"
• **with intraoperative CT scan**		Improved image quality; large segments of the spine can be visualized; can be used intraoperatively to confirm spinal implant positioning	Significant cost involved; physical integration into the operating room may pose a challenge. Requires special operating room table and other additional equipment
• **with preoperative CT scan**	Open surgery; can sometimes be used for MISS when matched with intraoperative image intensifier views	Good image quality; large segments of the spine can be visualized	Difficult to use for MISS; does not account for positional movement or shifting of the spine; requires postoperative CT scan to confirm implant positioning
Robotic surgery	Lumbar/thoracic spinal instrumentation procedures	Preoperative planning of instrumentation size and trajectories, planning of osteotomy procedures; no need to use cannulated screws or K-wires	Significant cost involved; training of staff and x-ray technician necessary; learning curve required; changes affecting the anatomy over time are not detected; requires postoperative CT scan to confirm instrumentation positioning. No real-time tracking

Table 1.3-1 Summary of the different imaging and navigation techniques in spine surgery.

tion guidance either for active guidance throughout surgery, or as a control at the end of the operative procedure.

More recently, stereotactic 2-D or 3-D imaging techniques have been developed and gained general acceptance in neurosurgery and in certain orthopedic trauma procedures. In computer-assisted surgery (CAS) a virtual representation of the surgeon's instruments is shown in relation to the patient's anatomy, which is displayed on a separate computer screen. Pre- or intraoperative CT scans or image intensifier images are used to generate a "virtual surgical reality". This surgical "GPS" requires the attachment of a reference array with reflective beads to the patient's spinal anatomy and to the surgical instrument that is to be tracked. The 2-D information obtained by two infrared cameras tracking these beads is converted into a 3-D representation based on the different reflective angles. The different types of CAS have been reviewed in a previous AO publication [102]. Tracking using electromagnetic instead of infrared technology is under evaluation, and has shown promising results [103, 104]. The types of spinal imaging and navigation currently available have been summarized in **Table 1.3-1**, while the potential benefits and possible drawbacks of CAS have been outlined in **Table 1.3-2**.

4.1 First-generation spinal navigation systems

The first-generation spinal navigation systems included 2-D navigation that relied on image intensification-based AP and lateral images to track an instrument's position in relation to the spinal anatomy. However, this "virtual image intensification" technology provided only 2-D information (**Fig 1.3-14**) [105]. The first-generation 3-D navigation systems used preoperative CT scans and required matching between the patient's bone anatomy and the scan through the surgical exposure of anatomical landmarks. Alternatively, intraoperative AP and lateral image intensification could be used to match the preoperative CT scan against the patient's anatomy in the operating room. The initial clinical reports, which described spinal instrumentation placement in the mid-1990s, showed promising results [106–109]. However, generally speaking, these early navigation systems were not well received by the surgical community; they were considered cumbersome, disruptive to the workflow in the operating room, and seemed to increase operating time.

4.2 Second-generation spinal navigation systems

The second-generation spinal navigation systems saw the light of day in 2002 when Siemens introduced the first portable cone beam CT scan—the "Iso-C 3-D" image guidance

Possible advantages	Possible disadvantages
Improves accuracy of implant placement and optimizes size of the implant used	The significant learning curve associated with these technologies for the surgeon and the operating room staff could constitute a drawback
Reduces radiation exposure to the surgeon and medical team	Significant cost involved in acquiring the basic equipment
Enables less invasive approaches through smaller access	Interruption of surgical "workflow"
Allows preoperative planning of implant size and trajectories, and planning of osteotomy procedures	Additional equipment and "surgical footprint" in the operating room
Allows intraoperative verification of screw placement accuracy (intraoperative scanners or image intensifier CT scan only)	Lack of scientific data in support of its clinical benefit
Minimizes the risk of wrong-level surgery	Limited imaging quality and field of view with the mobile 3-D imaging devices currently on the market
Decreases reoperation rate	Potential increase in operating room time
	Potential line-of-sight limitations for optical systems
	Concerns exist regarding accuracy, and interference with metallic instruments using electromagnetic navigation systems

Table 1.3-2 Possible advantages and disadvantages of CAS.

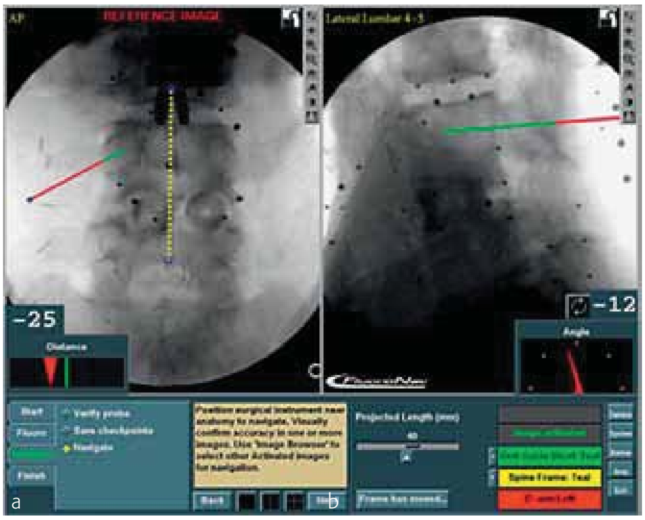


Fig 1.3-14a–b The "virtual fluoroscopy" navigation system used image intensification-based AP (**a**) and lateral (**b**) images to track an instrument's position in relation to the spinal anatomy, and provided only 2-D information [105].

system—which allowed the reformatting of intraoperatively acquired 2-D images into a 3-D dataset. This intraoperative CT scan could be used for navigation, and also to confirm the correct placement of instrumentation. Initial reports confirmed the usefulness of intraoperative 3-D imaging for the placement of spinal instrumentation and for the verification of correct implant positioning [110]. In 2006, the "O-arm" (Medtronic) was put on the market: it provided marginally better imaging quality, but a larger field of view. The portable isocentric C-arm and portable scanners offer the advantage that they can also be used as regular C-arms, however, their imaging quality is inferior to that of stationary CT scans. Computed 3-D navigation techniques in spinal instrumentation can improve the accuracy of screw placement, potentiate the ability to maximize the screw diameter relative to the pedicle, and reduce the risk of injury to critical neurovascular structures [103, 111–117]. A meta-analysis comparing computer-navigated versus noncomputer-assisted pedicle screw insertion (4814 navigated versus 3725 nonnavigated procedures) showed that there was a significantly lower risk of pedicle perforation for CAS pedicle screw insertion compared to nonnavigated insertion, with an overall pedicle perforation risk of 6% for CAS, and 15% for nonnavigated insertion [114]. However, this meta-analysis did not reveal a difference in total operative time or estimated blood loss when comparing the two techniques. In reviewing his experience, the present author compared navigated versus nonnavigated pedicle screw placement in 260 patients and 1434 screws with an evaluation of screw placement accuracy, screw size, and the complexity of surgery [118]. It was found that CAS was associated with improved screw placement accuracy, and that it was employed in cases with a higher degree of surgical complexity such as for MISS, cases of deformity, or revision surgery. Interestingly, it was also observed that CAS was associated with the use of larger pedicle screws and a higher screw-to-pedicle diameter ratio, a finding that can be explained by the possibility afforded by CAS to plan and therefore to optimize the diameter of the screw used, which is an important factor especially in patients with poor bone quality or deformity (**Fig 1.3-15**).

There is a degree of concern regarding the safety of current imaging and navigation techniques for MISS, particularly as regards the issue of radiation exposure and the use of K-wires over which cannulated pedicle screws are introduced. The use of K-wires involves a certain risk to the patient, as they can break or bend during the surgical procedure, and endanger visceral or vascular structures (**Fig 1.3-16**). In addition, surgical workflow using K-wires is a complicated process, involving the use of multiple instruments that are passed back and forth between the surgeon and the scrub nurse. However, when used intelligently, CAS can help to make spine surgery safer for the patient as well as for the surgeon and the operating room staff: The issue of radiation exposure in second-generation CAS for MISS has been addressed by Nottmeier et al [119]. In 25 MISS cases with 228 screws placed using portable cone-beam CT navigation, no radiation exposure to the surgeon was recorded. This means that K-wires cannot be used [120]. However, this problem has been circumvented by the present author and co-workers, who recently introduced a

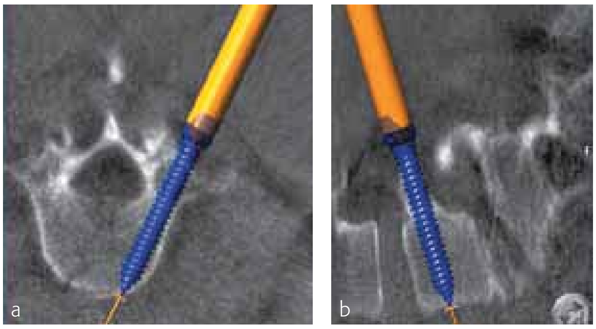


Fig 1.3-15a–b Axial (**a**) and sagittal (**b**) CT reconstruction of the lumbar region with planned pedicle screw placement.

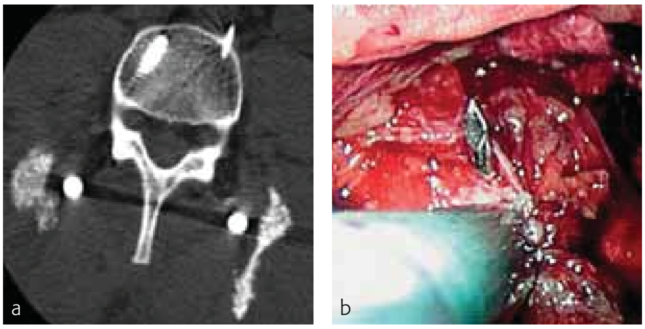


Fig 1.3-16a–b Views showing the inadvertent advancement of a K-wire during minimally invasive lumbar fusion surgery.

- **a** Axial view on CT lumbar imaging showing the tip of a broken K-wire perforating the anterior cortex of the vertebral body.
- **b** Intraoperative laparoscopic view during the retrieval procedure, revealing a K-wire tip that has breached the cortex into the surrounding soft tissue.

navigated guide tube that allows drilling, tapping and the placement of the final screw without the need for K-wires [121]. This instrument facilitates the workflow in the operating room by reducing the number of instruments that need to be navigated, and reduces the potential risks associated with current techniques for the insertion of percutaneous or mini-open pedicle screws by eliminating the need for K-wires (**Fig 1.3-17**).

4.3 Robotic spine surgery

Robotic surgery is being used for the placement of pedicle screws in the lumbar and thoracic spine [122–124]. For example, the Renaissance is a semiactive surgical guidance robot (Mazor Robotics Ltd, Caesarea, Israel) that has been designed to direct surgeons to predetermined locations along the spine. On a specially designed graphic user interface with specific software, the surgeon uses the preoperative CT scan to plan the trajectory of the screws. Intraoperative image intensifier x-rays with targeting devices are then matched with the CT-based virtual images, as well as the surgeon's plan. A clamp is attached to the spinous process, or a minimally invasive frame is mounted on the iliac crest and on a spinous process. The miniature robot is then attached to the clamp and/or frame. On the basis of combined CT scan and image intensifier data, the robot aligns itself to the desired entry point and trajectory, as dictated by the surgeon's preoperative plan (**Fig 1.3-18**). Studies reporting procedures using robotic surgery have found high levels of accuracy for implant placements. In a retrospective analysis of over 3,200 screws instrumented in 14 centers, Devito et al [125] reported 98% clinically acceptable implant positioning and 98.3% accuracy in a subset of 646 implants evaluated by postoperative CT scan. Robotic surgery has yielded promising results for percutaneous screw placement: Kantelhardt et al [126] compared conventional screw placement to open and percutaneous robotic surgery in 112 patients that underwent pedicle screw implantation, and found that the use of robotic guidance significantly increased screw placement accuracy, while cutting x-ray exposure by 50%. Patients also seem to experience a better perioperative course following percutaneous procedures. The downsides of robotic surgery include the fact that active tracking is not possible, and that implant accuracy can only be checked after surgery via CT scan.

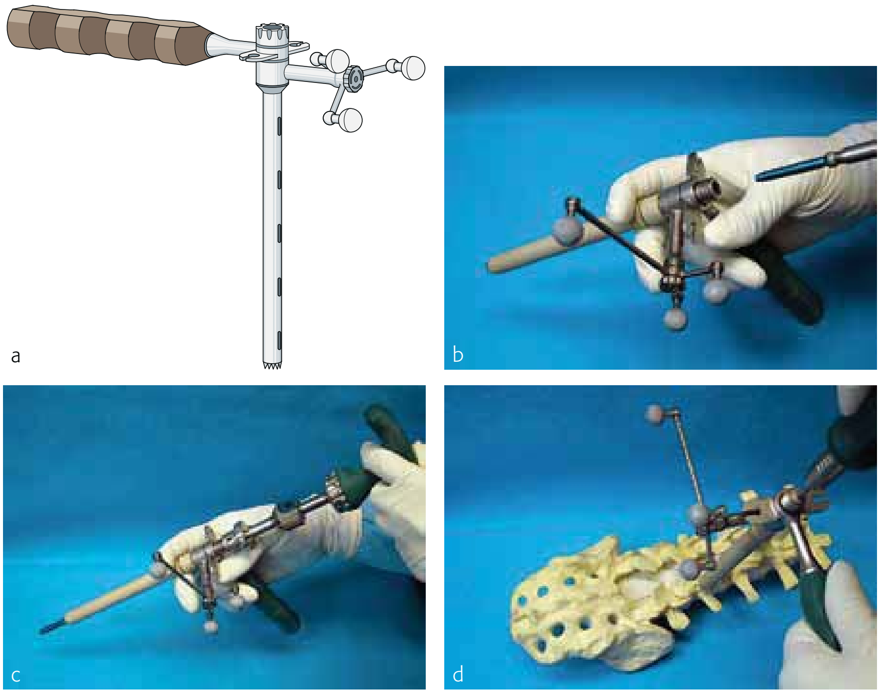


Fig 1.3-17a–d Views of the navigated guide tube, which eliminates the need for K-wires (**a**). The guide is comprised of a metal tube with a 10 mm outer diameter (**b**). An interface for attachment to an infrared reference array is positioned on the proximal end. A drill, tap, and then a pedicle screw without screwhead can be inserted through this guide tube.

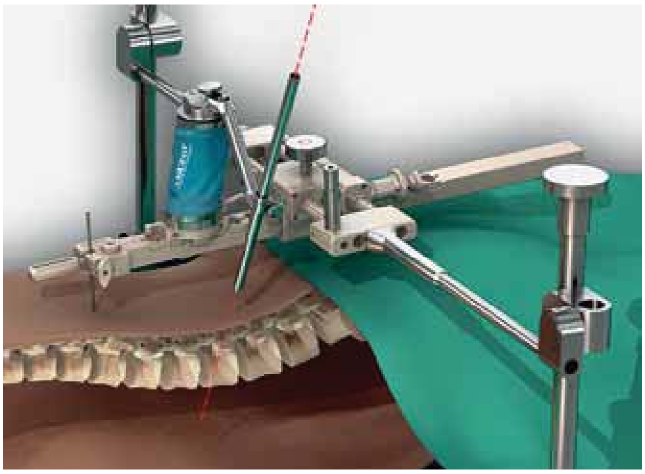


Fig 1.3-18 This image depicts the minimally invasive mounting platform for robotic surgery. A minimally invasive frame is mounted to the iliac crest and a spinous process. The miniature robot is attached to the frame. On the basis of combined CT scan and image intensifier data, the robot aligns itself to the desired entry point and trajectory, as dictated by the surgeon's preoperative plan. (Image courtesy of Mazor Robotics Ltd, Caesarea, Israel.)

4.4 Survey on the use of computer-assisted navigation in spine surgery

Computer-assisted surgery in spinal procedures clearly offers advantages over conventional surgery including greater screw placement accuracy, reduced radiation exposure, and better planning of the size and positioning of implants. Therefore it is surprising to note that CAS navigation has not been more widely accepted among spine surgeons. In this regard, the current viewpoint of spine surgeons regarding the use of CAS navigation in their everyday practice is an important issue, which has not yet been adequately investigated. Therefore AOSpine conducted a survey-based study to assess opinions on CAS navigation in order to determine the current global attitudes of surgeons on the use of computer-assisted navigation in spine surgery [127]. This study showed that despite the widespread distribution of navigation systems in North America and Europe, only 11% of surgeons use them on a routine basis. Surgeons dealing with high-volume procedures, those with a busy MISS practice, and neurosurgeons are more likely to use CAS. “Routine users” consider the accuracy, the potential to facilitate complex surgery, and the reduction in radiation exposure as being the main advantages. The lack of equipment, inadequate training, and high costs are the main reasons why "non-users" show a lack of interest in CAS.

The results of this survey send strong messages to the community of spine surgeons and their industrial partners:

1. In theory, surgeons generally view CAS as being of value, and almost 80% have a positive opinion of CAS.
2. In practice, current CAS systems do not meet surgeons' expectations in terms of time-saving, ease of use, and integration into the surgical workflow.
3. CAS systems have to be affordable and cost-efficient before they can be used on a more widespread scale.
4. Training has to be more readily available to overcome the demanding learning curve required for CAS. This training should not only address individual surgeons, but ideally should also include the surgical team in order to better integrate CAS into the existing workflow.
5. Conclusive scientific data are needed to more clearly determine the precision, radiation exposure levels, and cost-effectiveness of CAS. This will require the setting up of well-designed, prospective clinical trials.

In conclusion, computer-assisted navigation in spine surgery is a rapidly evolving field; and here, the current state of developments, which are still at an early stage in the evolution of this technology, has been summarized. More advanced and user-friendly systems that operate, for example, with true intraoperative CT scanners are becoming available and it will be interesting to see how these systems impact on the use and acceptance of computer-assisted navigation (**Fig 1.3-3**) [128, 129]. Spine surgeons will increasingly integrate the techniques of microscopic magnification, pre- and intraoperative planning, intraoperative real-time imaging, and 3-D navigation. In future, CAS will include more widespread access to better software and imaging technologies, and a combination of CAS with different imaging techniques and possibly intraoperative functional assessment, such as electrophysiological monitoring [130]. It is highly possible that the spine surgeons of the future will view CAS as the standard of care as far as imaging techniques are concerned.

5 Instruments and implants

The refinement of MISS techniques has necessitated the development of specialized instruments and implants, and guides for the instrumentation of all the anatomical regions of the spine via anterior, posterior, and lateral approaches. The availability of new implants and less invasive instruments, on the other hand, has also stimulated progress in the field of MISS.

5.1 Tubular retractor systems

Research has shown that the type of tissue retraction can have a significant impact on the pressure exerted on the muscles during surgery, on muscle ischemia, and on postoperative muscle strength and recovery from spine surgery [131]. The introduction of less invasive retractor systems has therefore helped to reduce iatrogenic muscle injury during surgery. For example, surgeons have used various types of specular retractors for standard microdiscectomy cases following a subperiosteal dissection [66] (**Fig 1.3-9**). In 1997, Smith and Foley [18, 19] described a microendoscopic discectomy procedure in the region of the lumbar spine, a modification of the original approach, in which endoscopes were used through tubular retractors to perform the discectomy. The METRx tubular retractor system (Medtronic, Minneapolis, USA) was introduced in 2003 and allowed the use of the microscope (**Fig 1.3-10**). In North America, tubular access has gained increasing popularity and is now used to treat pathologies in all regions of the spine via posterior and lateral approaches. Current retractor systems are either fixed-diameter or expandable, and can provide access to all parts of the spine. They are inserted over a set of muscle-splitting atraumatic dilators (**Fig 1.3-19**). The use of a K-wire is not recommended. In the thoracic and lumbar spine these retractor systems are also used for lateral exposure (**Fig 1.3-20**). Some retractors also incorporate fiber-optic illumination and endoscopic options. A black surface coating helps to minimize glare and reflection during surgery, and a unilateral bevel frequently allows better medial visualization and prevents muscle creep. In the lumbar spine, these retractors can be easily angled in order to improve access to the contralateral spinal canal (**Fig 1.3-11**). In the thoracic and cervical spine, however, this should be carried out with extreme caution, as the retractor wall may cause compression of the spinal cord and potentially lead to injury. In obese patients the standard tubular retractor may sometimes be too short, in which case an expandable retractor for the lateral transpsoas approach can be utilized (**Fig 1.3-20**).

Some surgeons prefer more versatile retractors that can be used for “mini-open” surgery. These retractors typically consist of several components that allow tissue blades to expand, and to expose larger portions of the anatomy (**Fig 1.3-21**). These instruments may be suitable for mini-open tumor resections and the placement of expandable cages via a posterior thoracolumbar approach. Almost every manufacturing company in the field of spine surgery now has their own retractor system.

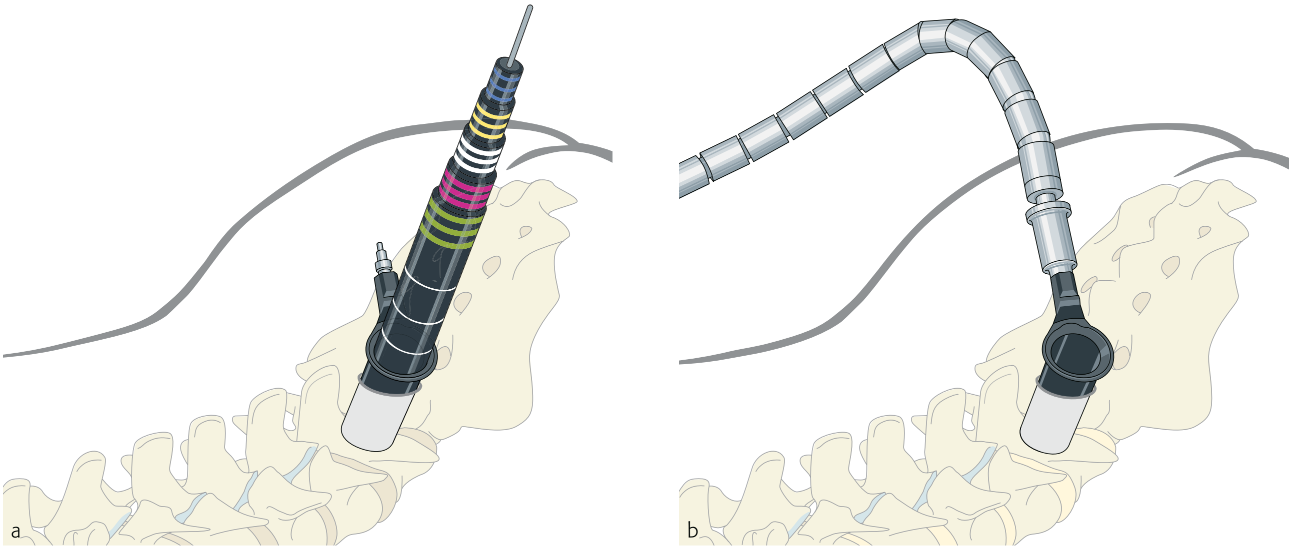


Fig 1.3-19a–b Fixed diameter retractor systems can provide access to all parts of the spine. They are inserted over a set of muscle-splitting atraumatic dilators (**a**), with flex arm (**b**).

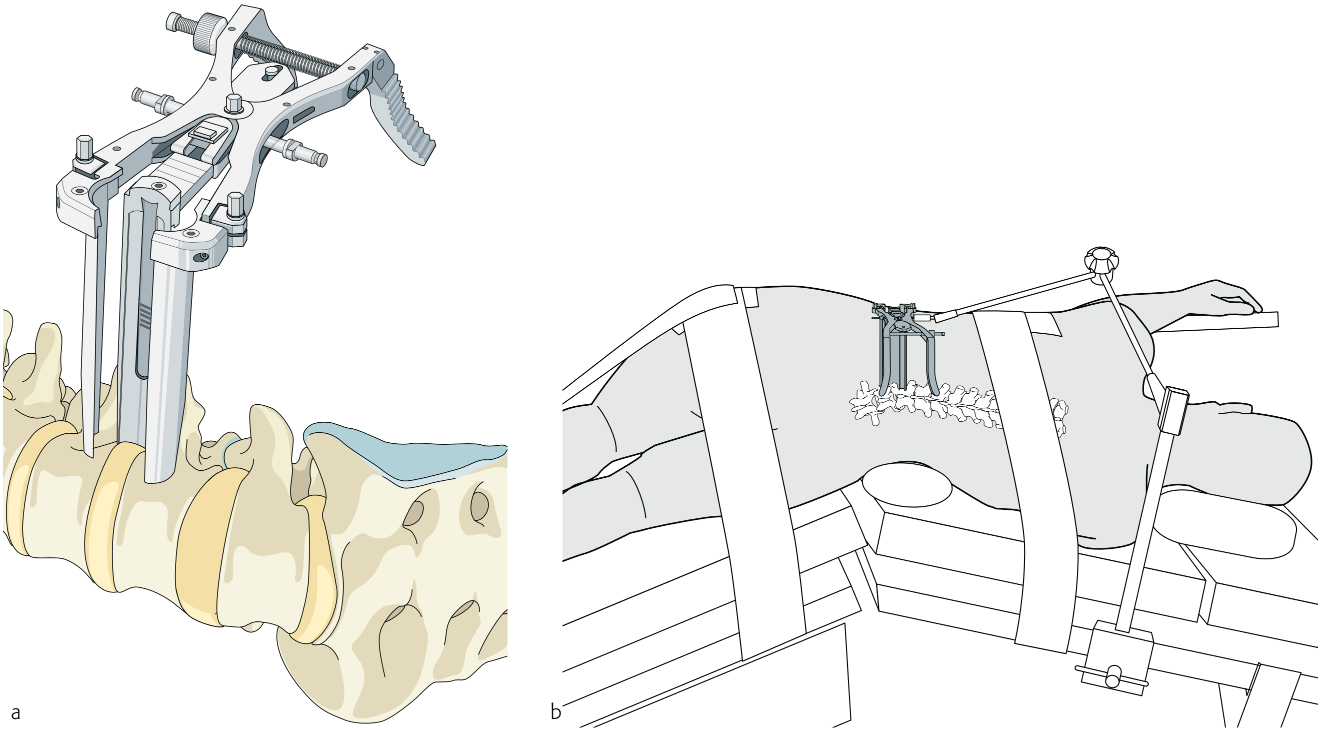


Fig 1.3-20a–b
a The Oracle retractor, part of a modular and comprehensive set of implants and instruments designed to support a direct lateral approach to the lumbar spine.
b The Oracle retractor and intraoperative patient positioning.

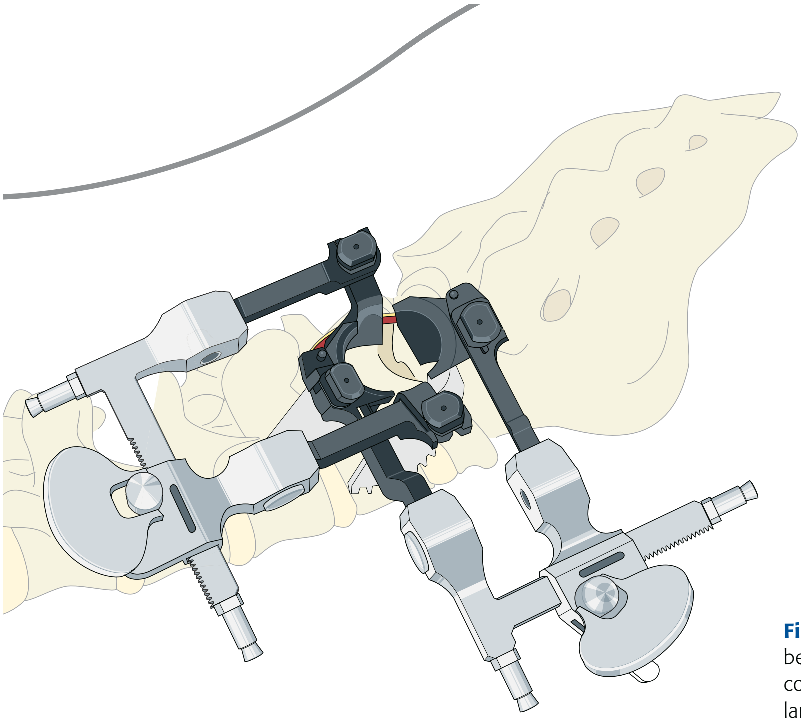


Fig 1.3-21 The more versatile type of retractor, which can be used for "mini-open" surgery, typically consists of several components that allow tissue blades to expand and expose larger portions of the anatomy.

The use of tubular or mini-open retractors made it necessary to develop special sets of bayonetted instruments to permit clear visualization of the spinal anatomy (**Fig 1.3-22a**). These include Kerrison rongeurs, curettes, pituitary rongeurs, Penfield probes, ball-tip probes, nerve hooks, dissectors, suction, bipolar forceps, to mention but a few. Pneumatic or electric high-speed drills with a curved drill attachment and drill bit can be used to remove bone (**Fig 1.3-22b**). The author prefers to use a 3 mm matchstick drill bit with a blunt tip that minimizes the risk of dural injury. The incidence of dural tears and operative time required are clearly dependent on the number of cases performed with this technique. The learning curve required is, however, complex and should be taken into consideration before counseling patients about the most suitable approach [75].

5.2 Minimally invasive posterior thoracolumbar instrumentation systems

Percutaneous or mini-open techniques for the insertion of pedicle screws aim at avoiding or minimizing surgical exposure and retractor-related muscle ischemia, and the development of atrophy and postoperative complications that are connected with conventional open surgery. An external spinal skeletal fixation system was developed in 1977 by Magerl in Switzerland [132] and has been used since then for the treatment of patients with spinal fractures and infection. This probably marked the first “minimally invasive” use of spinal instrumentation. The challenge during the early years was to develop a technique and instruments that would allow the minimally invasive placement of rods or plates under the dorsal muscular fascia to hold the pedicle screws and achieve a biomechanically stable construct. In 1995, Mathews and Long [133] reported on the placement of percutaneous pedicle screws connected to suprafascial, subcutaneous plates. In 2000, Lowery and Kulkarni [134] used suprafascial pedicle screw instrumentation that was later removed in conjunction with mini-open anterior interbody fusion, and reported good results in 8 patients. However, the longer moment arms associated with suprafascial rod placement aroused concerns regarding the overall stability of such a construct. Kevin Foley’s Sextant system [82, 83] then became available soon after, in 2001, and marked the beginning of modern minimally invasive thoracolumbar instrumentation. This and most later systems use an approach based on K-wire implantation using Jamshidi needles for screw placement. It was not until the most recent advances in spinal navigation were introduced that K-wires became unnecessary. The limitations of the Sextant system were mainly related to the arc-type rod insertion system that caused problems in patients with deformities, or in cases of multilevel fusion. Follow-up developments improved many of the shortcomings of the initial system. Many companies have now developed user-friendly, straightforward instrumentation systems and guides for percutaneous and mini-open pedicle screw placement (**Fig 1.3-23** and **Fig 1.3-24**).

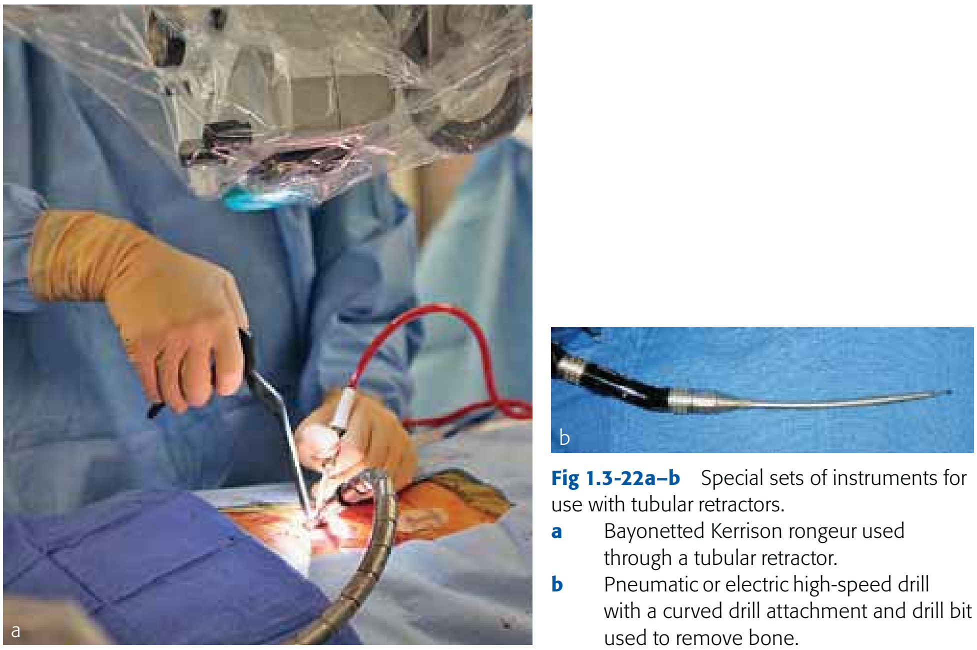
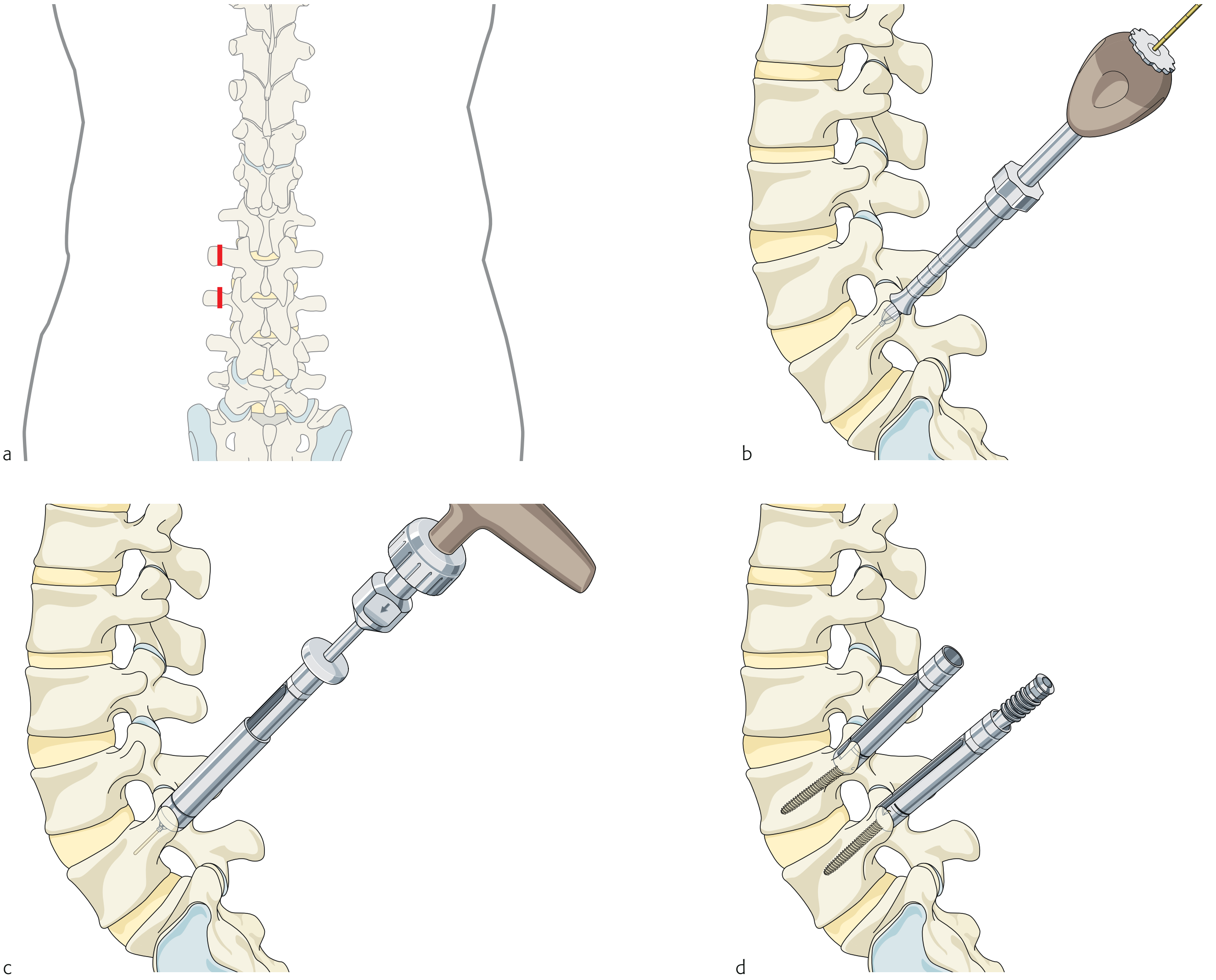


Fig 1.3-22a–b Special sets of instruments for use with tubular retractors.

- **a** Bayonetted Kerrison rongeur used through a tubular retractor.
- **b** Pneumatic or electric high-speed drill with a curved drill attachment and drill bit used to remove bone.



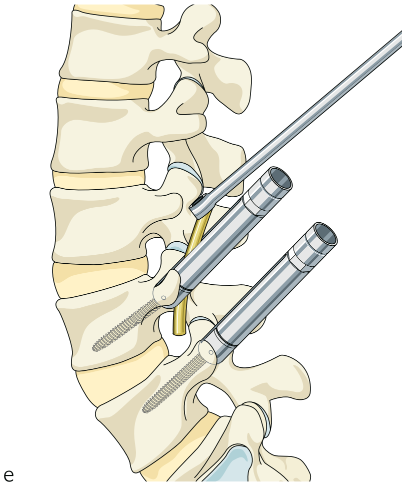
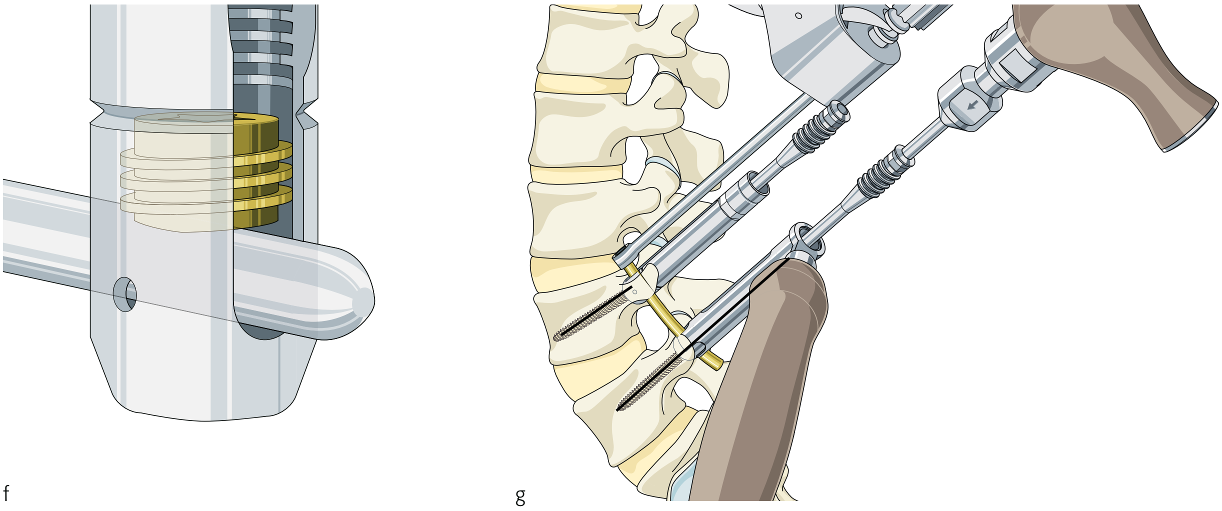


Fig 1.3-23a–h Outline of steps involved and instruments used in the insertion of percutaneous and/or mini-open pedicle screws.

- **a** Step 1: Small skin incisions are made just lateral to the lateral border of the facet joint, based on an intraoperative AP fluoroscopy view.
- **b–c** Step 2: Pedicle preparation is typically performed by placement of a K-wire using either AP and lateral fluoroscopy or other forms of navigation. As a next step an awl and then a tap can be used over the K-wire.
- **d–e** Step 3: Cannulated screws with extension sleeves are inserted over the K-wires and a rod is inserted.



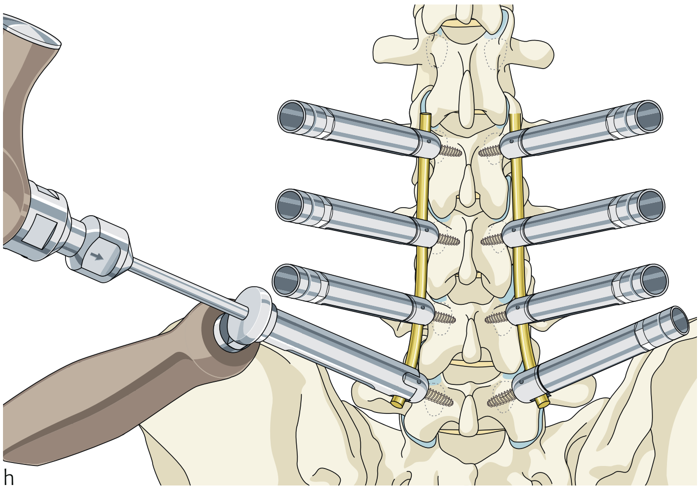


Fig 1.3-23a–h (cont) Outline of steps involved and instruments used in the insertion of percutaneous and/or mini-open pedicle screws.

f–g Step 4: Locking caps are then tightened in place using a counter-torque. Tightening of the locking caps reduces the rod.

h Multilevel constructs can be preferred using this technique.

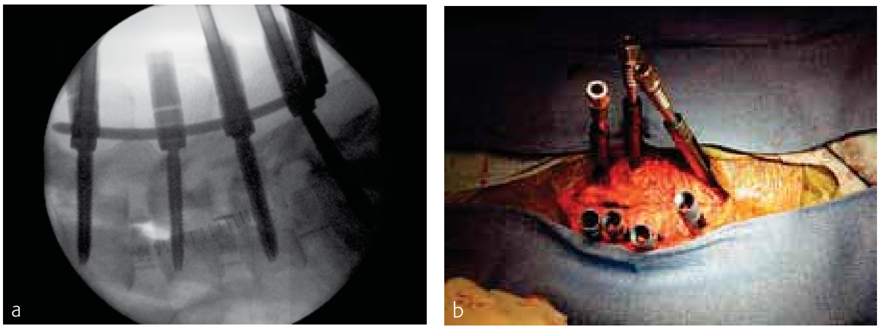


Fig 1.3-24a–b Views showing multilevel posterior MISS pedicle screw instrumentation after previous lateral transpsoas discectomy and fusion. In this case, the approach involved a midline skin incision with multiple small fascial incisions (**b**).

Also of interest is the use of percutaneous fixation in patients with metastatic spine disease following tumor resection, and in patients with traumatic fractures [135]. MISS screw fixation may offer advantages to these patients, who are more prone to infection, to avoid the wound healing difficulties associated with open surgery, or, in the case of tumor patients, after postoperative radiotherapy.

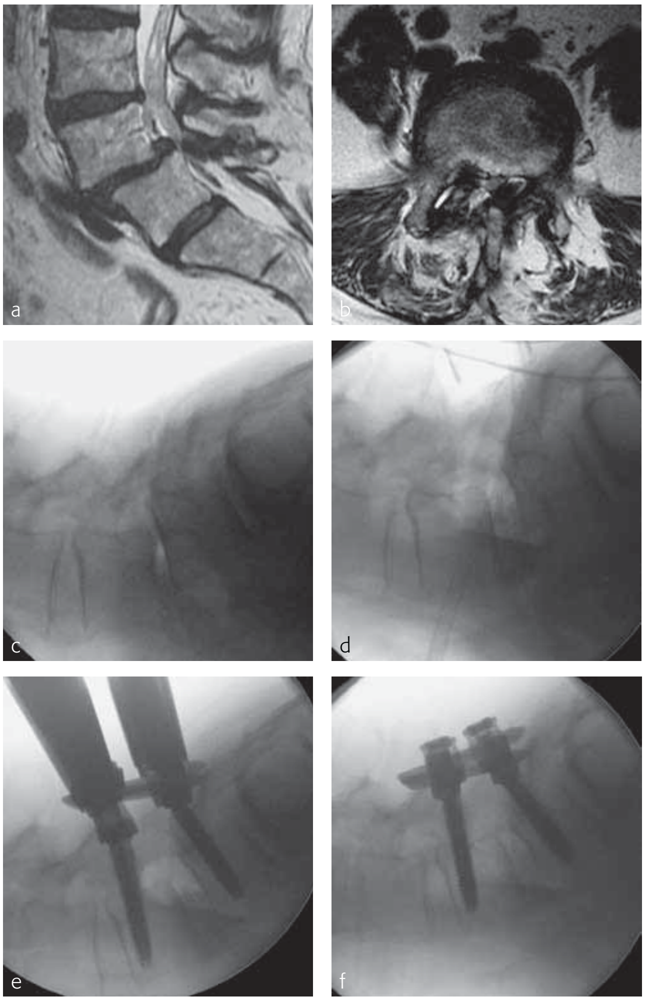


Fig 1.3-25a–f
a–b Views showing spondylolisthesis and severe stenosis after previous microdiscectomy at L4/5.
c Intraoperative image demonstrating grade II spondylolisthesis at L4/5.
d A laminectomy and discectomy were performed through a 22 mm tubular retractor. An expandable interbody PEEK cage was used to reestablish disc height and partially reduce the slip.
e–f Views showing MISS pedicle screw insertion. Placement of the rods and locking cap insertion allowed to completely reduce the slip.

The latest generation of top-loading thoracolumbar instrumentation systems offer the following advantages:

- Multilevel fixation from the thoracic spine to the iliac crest
- Allows to reduce deformities (**Fig 1.3-25**)
- The more lateral entry point between the transverse process and the facet joint, and the lateral to medial trajectory increase the pullout strength of the screw
- Lower rod profile is advantageous because the screw head can frequently be placed closer to the part of anatomy to be treated when compared to open systems
- Some manufacturing companies offer perforated pedicle screws for cement augmentation (**Fig 1.3-26**).

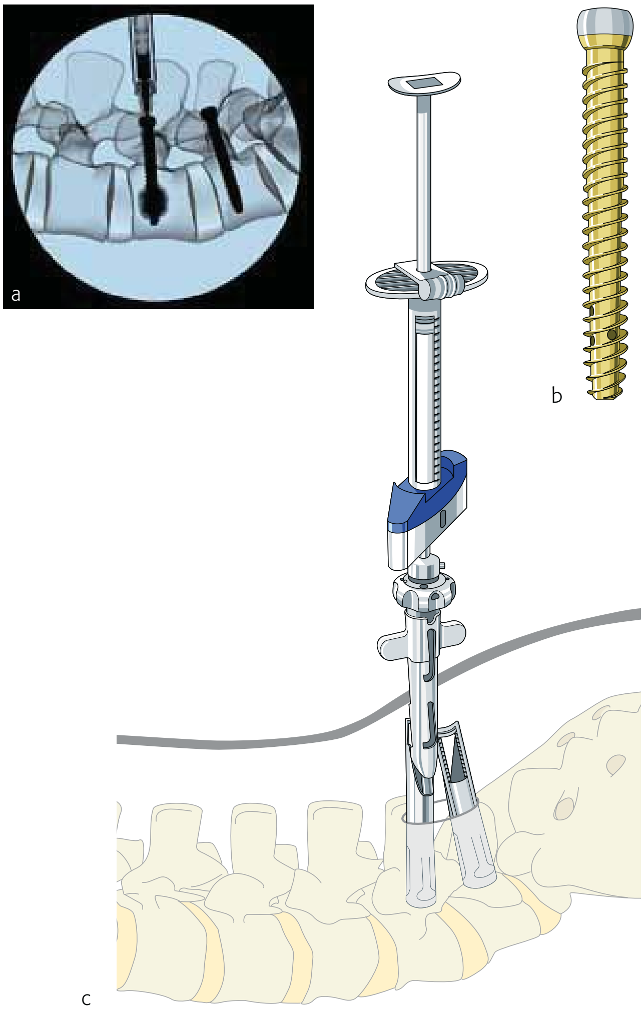


Fig 1.3-26a–c Cannulated and perforated pedicle screw for MISS cement augmentation.

Challenges and open questions include the following:

- Rod insertion in cases of multilevel procedures and deformities
- The choice of skin and fascial incision: multiple small skin incisions versus long midline incision or two paramedian incisions
- Screw stimulation can be problematic
- Some authors report a higher incidence of cranial facet violations with percutaneously placed pedicle screws [136]. CAS may be helpful in this regard
- Alignment and connection of lumbar pedicle screws with iliac instrumentation. Percutaneous S2 alar-iliac fixation has been described in the literature [137, 138]. It facilitates rod alignment and may offer a good alternative to traditional iliac screw placement, but more conclusive clinical data are needed before this technique can be fully recommended
- Posterolateral fusion is difficult or impossible with percutaneous or mini-open instrumentation. Therefore, the surgeon generally relies on anterior interbody fusion, apart from certain exceptions such as occasional cases of metastatic cancer or trauma
- The question of implant removal especially after fracture fixation without fusion is a subject of controversy. The author prefers to remove instrumentation after the fracture has healed.

The combination of MISS retractors, pedicle screw systems and interbody technology allows the treatment of pathologies that previously required more invasive surgery. For example, in the case of a 65-year-old patient with spondylolisthesis after previous microdiscectomy at L4/5, a laminectomy and discectomy was performed through a 22 mm tubular retractor (**Fig 1.3-25**). An expandable interbody polyetheretherketone (PEEK) cage was then used to reestablish disc height and partially reduce the slip. MISS pedicle screws were used to completely reduce the olisthesis and stabilize the level. In this case, bone autograft from the facetectomy was used in conjunction with iliac crest bone core harvested using a minimally invasive access bone-harvesting technique (**Fig 1.3-27**).

5.3 Other MISS instrumentation and implants

Interbody devices have been described for use with tubular retractors. For example, boomerang or banana-shaped interbody cages made of various materials can be inserted through tubular retractors and are now routinely used for MISS fusion (**Fig 1.3-28**). Although bone morphogenetic protein is frequently used for interbody fusion in MISS surgery [84], the present author prefers bone autograft from the facetectomy and/or iliac crest bone core harvested using a minimally invasive access bone-harvesting technique through the same or a separate incision (**Fig 1.3-27**). The development of expandable cage technology holds great promise for MISS, both for corpectomy, and also for interbody fusion (**Fig 1.3-29**). Expandable interbody cages can be inserted through tubular retractors and minimize the need for the retraction of neurological structures. Other interbody devices that can be considered less or minimally invasive include stand-alone ALIF implants with integrated screw systems that obviate the need for additional posterior fixation (**Fig 1.3-30**).

Fig 1.3-27 Two iliac-crest bone cores harvested using a minimally invasive access bone-harvesting system.

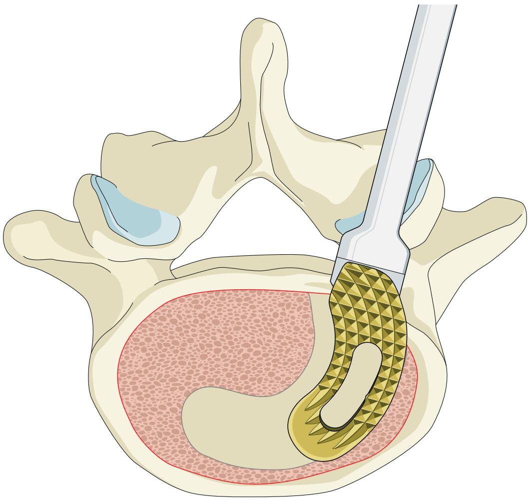


Fig 1.3-28 MISS interbody fusion. Schematic view of transforaminal posterior atraumatic lumbar cage system for MISS fusion.

Other MISS devices and techniques include:

- Percutaneous facet screw fixation to supplement anterior interbody fusion
- Interspinous distraction devices used for the treatment of mild to moderate spinal stenosis. Some devices can also be used for supplemental fixation and stabilization of the posterior spinous elements
- A presacral approach and instrumentation system to the lumbosacral spine without direct visualization has been developed and refined in recent years, and termed “axial lumbar interbody fusion” [99]
- Intervertebral stapling for spinal deformities
- Odontoid screw fixation systems
- C1/2 transarticular fixation systems
- Vertebral augmentation systems; vertebroplasty/kyphoplasty.

In summary, substantial advances in MISS have been made possible through the development and refinement of spinal instrumentation, implants, and technique guides. The future will likely see the incorporation of biologics and tissue engineering techniques into MISS technology. There is a great need to further explore and make further advances in the field of MISS. The surgeon/manufacturing industry interaction is crucial, and although current initiatives to regulate this relationship are important they should not interfere with the creative process that has allowed MISS to mature into a viable and highly successful discipline.

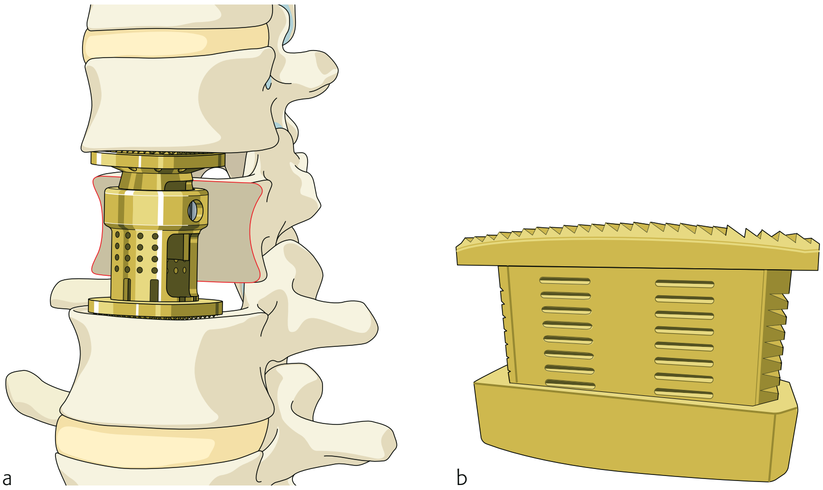


Fig 1.3-29a–b Expandable interbody cages, which limit the need for the retraction of neurological structures, can be inserted through tubular retractors and used for corpectomies (**a**) and also for discectomies and interbody fusion (**b**).

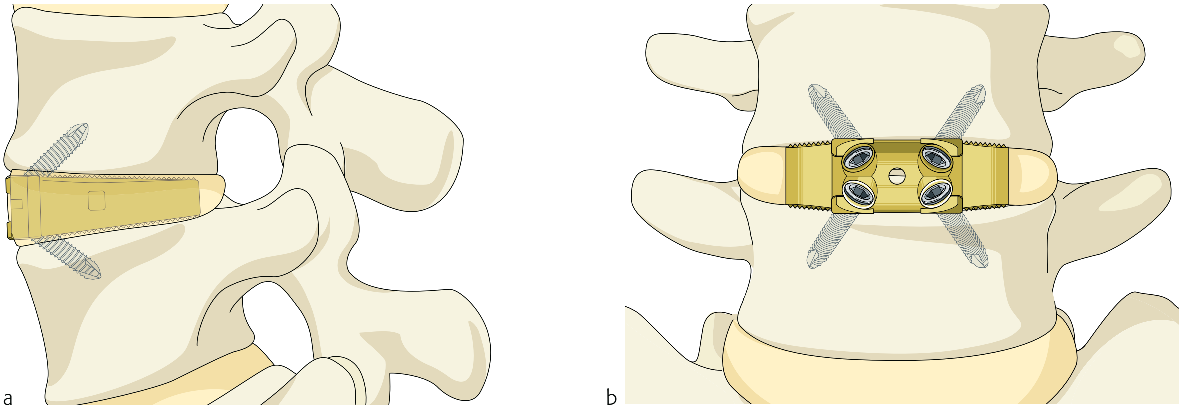


Fig 1.3-30a–b Stand-alone ALIF device incorporating an anterior fixation plate and a radiolucent interbody spacer. The design creates a zero profile construct and includes four locking screws that provide anterior fixation and stability.