18 Navigation of the Cervical, Thoracic and Lumbar Spine

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18.1 Introduction

Computer-assisted navigation (CAN) is a widely employed tool in spinal instrumentation surgery. It permits high-quality image guided placement of pedicle screws based on registration of preoperative or intraoperative spinal imaging data (e.g., preoperative or intraoperative CT images, intraoperative 3D fluoroscopy). The surgeon is thus provided with visual feedback showing the current planned screw placement trajectory superimposed on the imaging data of the patient. This is supposed to improve the safety and accuracy of pedicle screw placement and thus reduce complications potentially associated with screw misplacement, such as instability, neurological injury or revision surgery [1, 2].

CAN is applicable to the entire spine, i.e. for instrumentation of the cervical, thoracic and lumbosacral spine including the pelvis. The following case will demonstrate the use of CAN for spinal instrumentation.

The case will detail specific advantages and disadvantages of spinal navigation techniques with regard to:

- safety and accuracy
- image quality
- radiation exposure
- learning curve
- location (thoracolumbar versus cervical)

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18.2 Case Description

A 64-year-old male patient suffered from thoracic back pain after he fell while sailing his boat. His neurological examination was normal. A CT scan showed a vertebral compression fracture of Th 6 and signs of osteoporosis (Fig. 18.1). The MRI scan was consistent with a recent injury (Fig. 18.2). There was no neural compression.

The patient had a history of cigarette smoking (50 pack years) and was otherwise healthy.

Analgesics did not provide sufficient pain relief. Instead, after a few weeks, the pain was increasing. The relative indication for surgery was discussed with the patient in detail. Taking medical history and age into account, it was eventually decided to proceed with minimally-invasive percutaneous posterior instrumentation. As in any spinal instrumentation performed in our department, CAN was used for pedicle screw placement (Figs. 18.3, 18.4, and 18.5).

As a first step, the navigation reference array was tightly attached to a spinous process via a small incision of skin and fascia (Fig. 18.3). Then, a 3D-scan was acquired (Fig. 18.4). During scanning,

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Fig. 18.1 CT Sagittal (left) and axial (right) slices of a CT scan showing a compression fracture of the vertebral body of Th 6. Both endplates are affected (white arrows), and there is height loss suggesting involvement of the posterior wall as well (red arrows). There is decreased cortical thickness as well as loss of trabecular bone structure, consistent with osteoporosis. The pedicles are intact, and there is no bony narrowing of the spinal canal

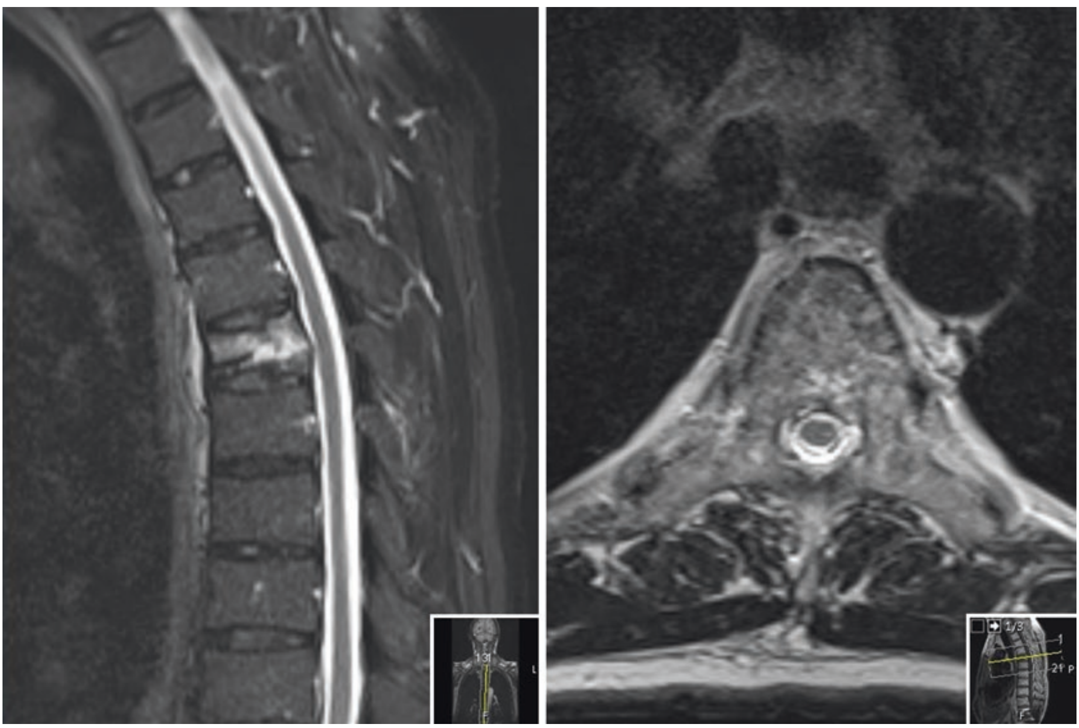

Fig. 18.2 MRI Sagittal (left) and axial (right) MRI slices. A STIR (Short Tau Inversion Recovery) sequence was acquired, providing sensitivity to bone marrow edema. There is substantial edema in the vertebral body of Th 6, suggestive of a recent injury. There is no significant spinal canal stenosis associated with the fracture

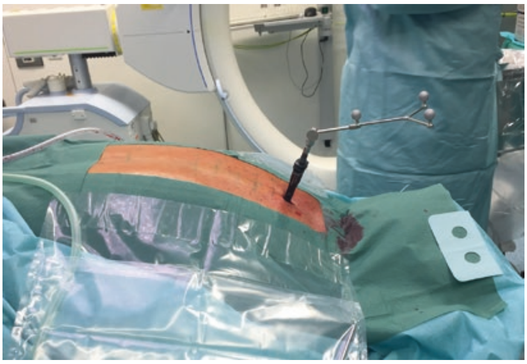

Fig. 18.3 Navigation reference array. This intraoperative picture shows the navigation reference array. Care must be taken to ensure tight attachment to the spine, which is usually achieved by clamping to a spinous process that is exposed via a small incision of the skin and fascia. The marker spheres can be detected by the navigation system's camera

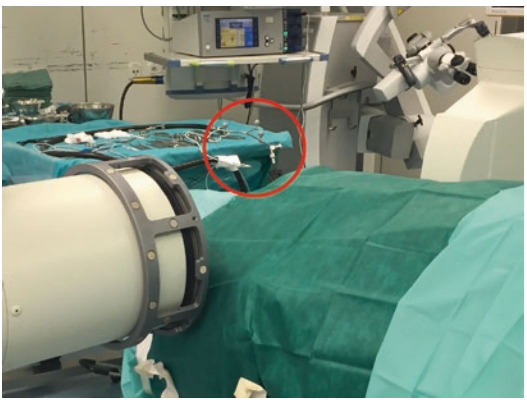

Fig. 18.4 Acquisition of 3D-fluoroscopy scan. The surgical field is covered to maintain sterility. The marker spheres (red circle) remain exposed to the field of view of the navigation system's camera, permitting 3D registration of the patient's anatomy with the acquired imaging data. Anesthesia should provide apnea during scanning to prevent movement artifacts

the OR staff could leave the operating room, eliminating radiation exposure. Anesthesia provided apnea to prevent movement artifacts after sufficient preoxigenation of the patient. Both the marker spheres of the reference array and the C-arm can be detected by the camera of the navigation system, permitting registration of the patient's anatomy with the acquired imaging data. The drill guide can be detected by the navigation system as well, enabling multiplanar visualization of the tip of the drill and

Fig. 18.5 Navigated pedicle screw placement. This intraoperative picture shows navigated placement of pedicle screws. Using a navigated drill guide with marker spheres that are detectable by the navigation system's camera, the tip of the drill as well as the current drilling trajectory can be superimposed on the 3D image set in three planes. This enables the surgeon to choose the ideal drilling trajectory based on visual feedback. After drilling, a k-wire is placed into the drill hole. The screw can then be placed via the k-wire along the navigated trajectory

the current drilling trajectory superimposed on the intraoperative 3D scan (Fig. 18.5). First, we confirmed that the registration succeeded by making sure that intraoperative landmarks (e.g., spinous processes) correspond to the respective structure in the image set. Then, pedicle screws could be placed without the need to expose anatomical landmarks, permitting a minimally invasive percutaneous approach while maintaining maximum accuracy. There was no need to perform imaging during screw placement, reducing the radiation exposure to surgeon and patient to a minimum as opposed to standard free-hand placement procedures using biplanar intraoperative fluoroscopy.

Pedicle screws were placed bilaterally in Th 4, 5, 7 and 8. A final control 3D-scan confirmed accurate placement of the screws. Prior to cement augmentation with PMMA. As a last step, rods were implanted using the caudal most existing skin incision.

There were no adverse events during or after surgery. The patient reported immediate pain relief. Standing radiography confirmed correct positioning of the implant (Fig. 18.6).

The patient was mobilized on the day of surgery and discharged home after 2 days. He was

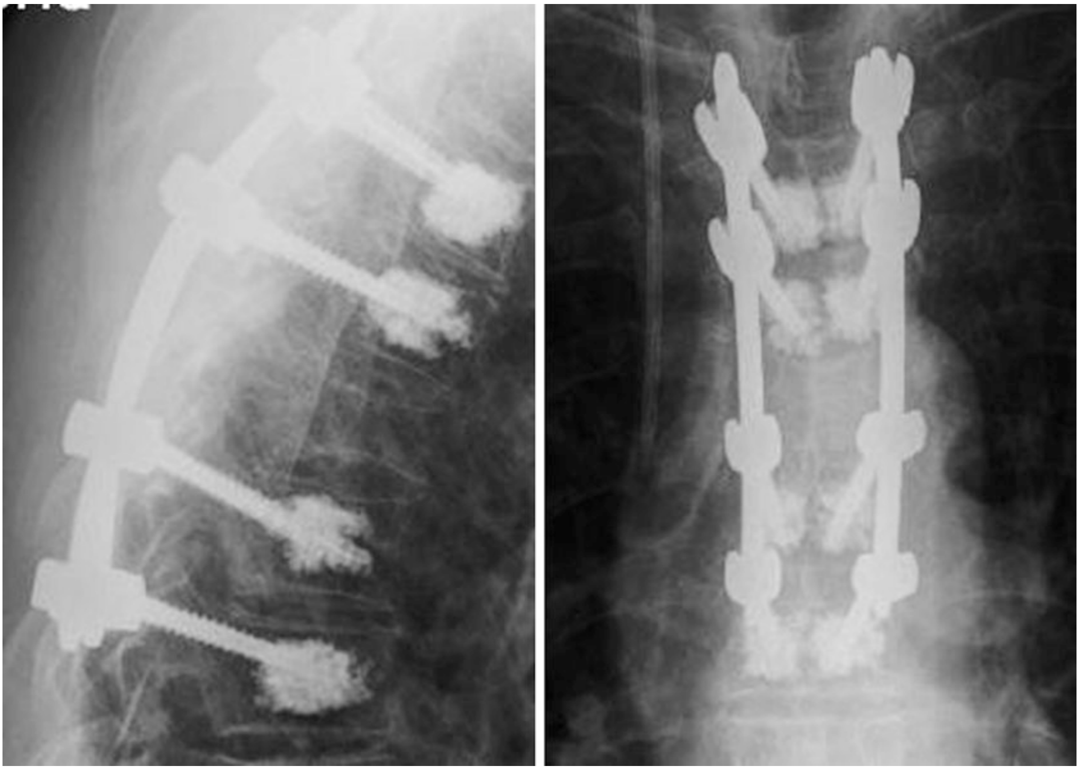

Fig. 18.6 Postoperative lateral (left) and a.p. (right) standing radiography confirm correct placement of the instrumentation system

referred to an endocrinologist to further investigate and treat the newly diagnosed osteoporosis.

18.3 Discussion of the Case

We present a standard case with instrumentation of the thoracic spine. We chose to use CAN for pedicle screw placement, as we do for any spinal instrumentation surgery involving pedicle screw placement in our department.

18.3.1 Navigation Techniques: Advantages and Disadvantages

18.3.1.1 Preop CT imaging for intraoperative Navigation

There are several CAN systems available, and there are also methodical differences. An important variable is the imaging modality. Imaging can be acquired preoperatively or intraoperatively. Excellent image quality is the biggest advantage of preoperative imaging (e.g., a CT scan.) A downside of preoperative imaging, however, is patient positioning for preoperative CT acquisition wich usually is supine in constrast to the prone position during surgery. This might be a source of possible imaging inaccuracy during surgery.

This technique works by point-by-point surface registration of the posterior vertebral lamina with a navigation probe (see Figs. 18.7, 18.8, and 18.9).

This way every vertebral level needs to be registered individually prior to instrumentation. This might take longer than using navigation systems working with intraoperative image acquisition techniques which usually have an automated registration.

Percutaneous minimally-invasive procedures can therefore not be performed since the posterior spinal elements need to be exposed with this technique. The superior image quality of this technique is of particular importance in the cervical spine where any PS inaccuracy can have devastating effects (vertebral artery injury if PS is placed too laterally or spinal cord injury in medial displacements). We therefore prefer CT-region matching with preoperative CT imaging for posterior instrumentations of the c-spine. Of importance is the high mobility of the c-spine in contrast to the thoracolumbar spine. We highly recommend to register every to be navigated vertebra individually prior to pedicle screw placement to enable for the highest possible accuracy.

Obviously, as in the present case, a percutaneous approach is not compatible with surface matching that requires exposure of at least the laminae of the vertebrae to be instrumented.

With the advent of intraoperative CT scanners this option might become obsolete one day, if these devices will hopefully become more affordable in the future.

Fig. 18.7 Marked to be navigated posterior lamina of the cervical spine for CT-region matching navigation

18.3.1.2 Intraoperative 3D-fluoroscopy guided Navigation

Besides preop and intraop CT imaging most other navigation systems are based on intraoperative 3D-fluoroscopic image-guidance. Images are

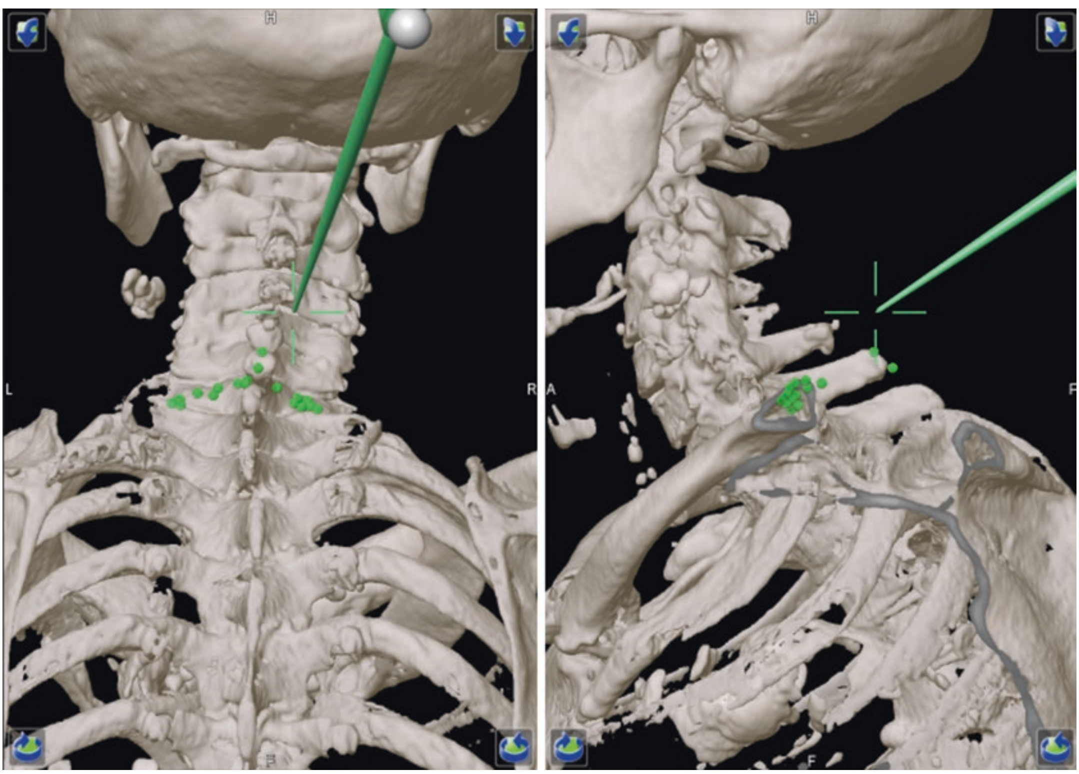

Fig. 18.8 Point-by-point registration of a posterior cervical spine lamina for CT-region matching registration

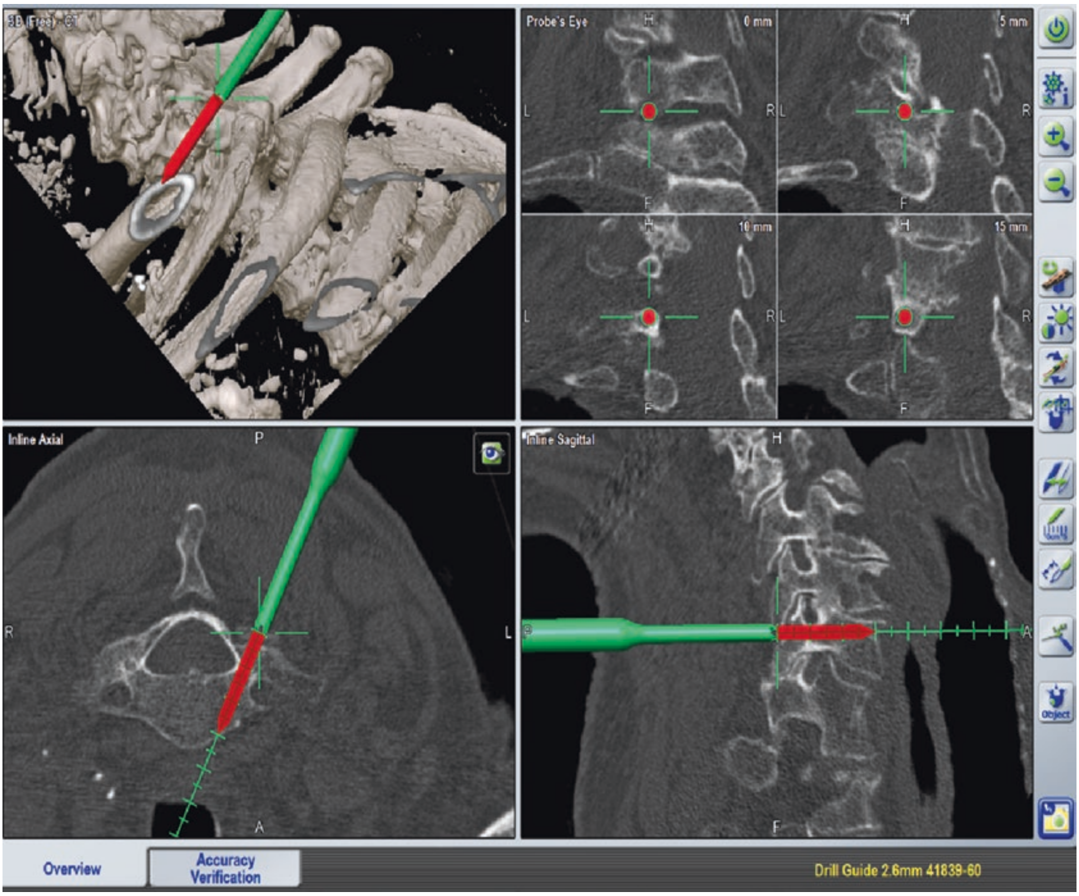

Fig. 18.9 Intraoperative CT-region matching based pedicle screw trajectory of the cervical spine

acquired intraoperatively after attachment of the reference array and registered automatically. This technique is therefore suitable for open as well as percutaneous minimally-invasive procedures. Depending on the system there are differences in image-quality and size of the field of view. In general image quality and gantry size are inferior to iCT, but these systems are less expensive.

For thoracolumbar instrumentations, we prefer intraoperative imaging for several reasons. The relatively low mobility of the thoracolumbar spine permits using one single scan for instrumentation of several segments. Available 3D-fluoroscopy imaging systems can acquire the entire lumbar spine and up to six or seven thoracic segments with one scan and modern systems with a larger field of view even enable navigation of the pelvis for S2-ala iliac screw placement. This makes intraoperative imaging the more efficient alternative when compared to surface matching in these cases. Moreover, the direct registration of the imaging data possibly provides higher accuracy than surface matching in the thoracolumbar spine, where post-scan-movements are less likely than in the cervical spine. This is consistent with the findings of a recent study comparing intraoperative with preoperative imaging – based navigation in scoliosis surgery [3].

Image quality which is up to date inferior to CT-imaging makes these systems less suitable for use in the cervical spine and the cervicothoracic region.

Patients with pathologically reduced bone mineral density or excessive obesity might also hamper image quality and reduce safety and accuracy.

18.3.1.3 Intraoperativ CT

Intraoperative CT definitely has advantages over other navigation systems. It produces the highest image quality, has the largest gantry and the largest field of view compared to other systems theoretically enabling navigation of the entire spine including the pelvis with one scan with a comparably low radiation dose. But of course, these systems come with a price and are the most expensive ones on the market today.

High investment costs are the downside of all intraoperative navigation systems available at the moment.

In general, CAN has many substantial advantages, accuracy being the obvious one. Based on more than 20 clinical trials that evaluated pedicle screw placement using CAN, there is no doubt that the procedure is safe and that it increases the accuracy of pedicle screw placement when compared to standard freehand (FH) pedicle screw instrumentation [1]. Whether this translates into a better clinical outcome for the patient has been analyzed by several meta-analyses. Most studies found only a trend towards improvement in clinically relevant outcome parameters, such as screw revision rates or neurological injury [1, 2, 4]. It has been argued that the difficulty in proving clinically relevant superiority of CAN over FH may be due to the known high success rates and safety profile of the latter method [1, 5]. Moreover, the variety of different CAN platforms adds heterogeneity to results in most studies [1]. Accordingly, using strict exclusion criteria, another meta-analysis found a significantly lower rate of screw-related complications in the CAN cohort as compared to the FH cohort [1, 6]. It can be assumed that future studies will add further evidence supporting the logical assumption that prevention of misplaced pedicle screws is beneficial to the patient.

Our case illustrates that CAN facilitates pedicle screw placement substantially. Mid-thoracic screws were placed through small skin / fascia incisions without the need to expose anatomical landmarks for orientation, as is usually required in FH instrumentation. One could argue that, given the technical effort associated with CAN, it should be limited to the most difficult cases only. However, in addition to providing facilitation and accuracy, there are two more facts supporting use of CAN whenever possible: First, CAN has been shown to eliminate radiation exposure to the OR staff and to significantly reduce the patient's effective dose of radiation exposure in a randomized prospective trial [7]. Thus, withholding it from patients and personnel is at least questionable. Finally, CAN is associated with a learning curve [8]. This needs to be overcome to fully benefit from its advantages, requiring its application on a regular basis.

Consequently, we argue that CAN should be implemented as standard procedure in the daily surgical routine of any spine surgery center [9].

As holds true for all navigation systems is the obligation of the surgeon to know the patient's anatomy and to check plausibility and accuracy of the navigation system repeatedly during surgery. All systems are prone to inaccuracy for example by unintended displacement or loosening of the reference array. Inaccuracy also increases with increasing distance of the reference array to the camera. The surgeon also needs to check the line of sight. Unnoticed blockage of the line of sight by an instrument, the surgeon or the instrumenting nurse during pedicle screw placement is also a possible source of inaccuracy.

Navigation therefore does not guarantee for accurate pedicle screw placement if these basic rules are not followed.

18.4 Conclusions and Take Home Message

CAN is a tool designed to assist in pedicle screw placement in spinal instrumentation surgery. It can facilitate the procedure, improve its accuracy, reduce the rate of revision surgeries by misplaced pedicle screws and possibly prevent associated complications. With CAN, radiation exposure is reduced for the patient and for the medical personnel. It is applicable to the cervical, thoracic and lumbar spine and to both open and minimally invasive approaches. However, there are technical nuances that are associated with advantages and disadvantages specific for the spinal region. Knowledge of the theory and technical application of CAN is crucial – inaccurate registration is useless, and the surgeon must be able to realize inaccurate navigation at any time during surgery. There is a learning curve for CAN, so it should be employed daily, on a regular basis. CAN should be used in spinal instrumentation surgery whenever possible.

- Computer-assisted navigation (CAN) is a useful tool in spinal instrumentation
- CAN increases pedicle screw placement accuracy, potentially leading to a better clinical outcome
- CAN significantly reduces the rate of revision surgeries due to PS screw misplacements
- CAN significantly reduces radiation exposure to medical staff and the patient
- CAN is useless when the registration fails, so knowledge of the theory and application of the technique is crucial
- CAN needs to be practiced, and there is a learning curve
- CAN should be standard in spinal instrumentation surgery
- CAN facilitates minimally-invasive spine procedures, esp. instrumentation
- CAN facilitates the increased use of percutaneous minimally-invasive procedures. Minimizing approach-related morbidity is crucial to reduce wound healing problems and infections in spinal tumor patients needing postoperative adjuvant radiation therapy
- CAN can help to better understand the complex anatomy of the spine

Pearls and Pitfalls
- Check plausibility and accuracy repeatedly
- Know the anatomy
- Do not entirely rely on the navigation
- Intraop imaging is still virtual reality
- Accuracy decreases with increasing distance of the reference array to the camera
- Unnoticed/unintended movement of the reference array during surgery can cause inaccurate pedicle screw placement
- Do not attach reference array on lamina of lytic or mobile spinous processes
- Avoid too tight attachment of the reference array, which might break the spinous process
- Ensure an unobstructed line of sight
- CT-region matching is not suitable for percutaneous procedures

Editorial Comment

Everything that needs to be known about spinal navigation today is described and discussed in this chapter by the senior author (YR), who has done extensive clinical research work in this field. Similar to chapter 7 the authors have chosen a non-degenerative case, which is not important in this instance, because technical principles are presented applicable to all pathologies. It is the editors' strong belief, that in the future navigation will be an integral part of all spinal surgeries/instrumentations. It is proven that it increases safety for the patient as well as the surgeon, by reducing misplacement rates and radiation exposure. It may be that these advantages are not "a big step", because adequate accuracy can also be achieved with a free-hand technique. However, one should remember, that progress in clinical science and ultimately patient care comes always in small steps. To translate the corresponding German phrase verbatim would be "the better is the enemy of the good". Neurosurgeons with a cranial focus are familiar with this development from an outsider technique to a standard of care over a time span of 20 plus years, because the beginnings of cranial navigation dates back to the late 80ies/early 90ies. The authors correctly convey very important principles for a successful implementation of spinal navigation. These include:

(a) Mandatory use in all (routine) cases for a successful integration into clinical routine to create confidence with the technique in the difficult cases, where it is actually needed and can be then applied without distracting from the actual surgery. Using it in the difficult case only is the most fatal mistake to be made.
(b) Resilience to the hardships of the learning curve needs to be anticipated and communicated to all team members to increase acceptance.

(c) The pitfalls of the technique need to be known and carefully avoided. As a rule of thumb, inaccuracies despite navigation are basically always related to the human factor and not the machine.

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