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Total navigation in spine surgery; a concise guide to eliminate fluoroscopy using a portable intraoperative-CT 3D navigation system

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IRB approval: Our local institutional review board approved the study and informed consent was obtained from all patients before surgery.

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Abbreviations
ELIF: Extreme Lateral Interbody Fusion
EMG: Electromyography
iCT NAV: Intraoperative Computer Tomography Navigation
MIS-TLIF: Minimally Invasive – Trans Foraminal Interbody Fusion
MISS: Minimally Invasive Spine Surgery
NAV: Image Guided Navigation
OR: Operating/Operating Room
RA: Reference Array

Keywords: Spine, navigation, minimally invasive spine surgery, CT, fusion, neural decompression
Abstract

Background: Portable intraoperative computed tomography (iCT) with integrated 3D navigation offers new opportunities for more precise navigation in spinal surgery, eliminates radiation exposure for the surgical team and accelerates surgical workflows. We present the concept of “total navigation” using iCT NAV in spinal surgery. Therefore, we propose a step-by-step guideline demonstrating how total navigation can eliminate fluoroscopy with time efficient workflows integrating iCT NAV into daily practice.

Methods: A prospective study was conducted on collected data from patients undergoing iCT NAV-guided spine surgery. Number of scans, radiation exposure and workflow of iCT NAV (instrumentation, cage placement, localization, etc.) were documented. Finally, the accuracy of pedicle screws as well as time for instrumentation was determined.

Results: iCT NAV was successfully performed in 117 cases for various indications and in all regions of the spine. 61% of cases were performed in a minimally invasive manner. Navigation was utilized for skin incision, localization of index level and verification of implant position. iCT NAV was used to evaluate neural decompression achieved in spinal fusion surgeries. Total navigation eliminates fluoroscopy in 75%, thus reducing staff radiation exposure entirely. The average time for iCT NAV setup and pedicle screw insertion was 12.1 and 3.1 minutes, respectively achieving a pedicle screw accuracy of 99%.

Conclusions: Total navigation makes spine surgery safer, more accurate and enhances efficient and reproducible workflows. Fluoroscopy and radiation exposure for the surgical staff can be eliminated in the majority of cases.

Keywords: navigation, CT, minimally invasive spine surgery, neural decompression, spine, degenerative
Introduction

As minimally invasive spine surgery (MISS) constantly progresses, spine surgeons increasingly rely on advanced image guided navigation (NAV). However, NAV systems still seem to decelerate surgical workflow, which limits its versatility and applicability in the broad field (1). Recent studies suggest intraoperative CT-guided (iCT) NAV provides benefits that outweigh these drawbacks, including reducing radiation exposure, saving operative (OR) time and improving the accuracy of instrumentation (2-4). The portable iCT AIRO NAV (Brainlab AG, Feldkirchen, Germany) is a state-of-the-art iCT which offers new opportunities for more precise navigation in spinal surgery, while at the same time accelerating surgical workflow particularly in MISS when the anatomy is altered and orientation may be difficult (5-7).

Recently, we have introduced the concept of total navigation in MIS-TLIF (8). Total navigation employs intraoperative 3D navigation combined with the latest-generation portable iCT in all steps of spine surgery. Application of total navigation results in complete elimination of radiation exposure for the surgical staff, elimination of K-wires for instrumentation and elimination of the pedicle probe.

Here we propose a “step-by-step” guide for the application of total navigation in spine surgery which can be used to successfully implement this technique into daily spine surgery practice. Additionally, this manuscript can be considered as a complimentary part to our recently published MISS guide, if “total navigation through tubular retractors” is intended (9).

The aim of the present study was to prospectively review our first 117 cases using iCT NAV for total navigation, and to summarize our experiences regarding surgical workflow, pedicle screw accuracy and complications into a sufficient guideline. Case examples demonstrating the versatility of this technology are provided in the supplemental digital content. Additionally, an instructional step-by-step illustrative material on how to perform a totally navigated MIS-TLIF is provided.
Material and Methods

Indications for total navigation

A prospective single-center study of patients undergoing iCT NAV-guided spine surgery with single- or multilevel spinal disorders (occipital-cervical to lumbar-sacral), between November 2014 and January 2016 was conducted, including diverse pathologies (degenerative, trauma, neoplasm, deformity, etc.) as demonstrated in Table 1. Demographic data including patient history, age, sex, and comorbidities were documented.

Operating room setup

The iCT-guided NAV included the Airo® CT scanner, an image-guidance system, an infrared tracking camera navigation system (Brainlab CurveTM, Brainlab AG, Feldkirchen, Germany) and a patient reference array (RA) (Brainlab AG, Feldkirchen, Germany). The design of the Airo® CT scanner combined a large gantry opening (107cm) with a slim gantry (30.5cm x 38cm) and a small footprint (1.5m²). The suspension-controlled electrical drive system allowed the machinery to be moved around the operating room (OR). A mobile, radiolucent carbon fiber table (Trumpf TruSystem 7500, TRUMPF Inc., Farmington, Connecticut, USA) was attached to the gantry during surgery. Airo® and CurveTM systems were connected to an automatic image-transfer device and an image-patient co-registration that assisted in navigation. Pre- or manually calibrated instruments could be used with navigation for enhanced workflow.

Setup of the iCT NAV for total navigation:

1. Before surgery, the iCT NAV is positioned parallel with the rail system and the gantry, facing anesthesia (Figure 1A).
2. After the patient is anesthetized on a transport bed parallel to the gantry, the gantry of the portable iCT system is rotated perpendicular to the rails into the scan position (Figure 1B).
3. Hereafter, a Trumpf carbon fiber tabletop with a T3 frame is connected to the Trumpf column on the integrated rail system.
4. Intubation and insertion of the needle electrodes for EMG monitoring is conducted, followed by flipping the patient onto the T3 frame.
5. Next, the patient is positioned on and taped to the table. Adequate taping is important since it minimizes anatomical displacement, especially in obese patients. Care has to be taken not to tape too tightly in order to avoid skin necrosis or pressure points (Figure 1B Supplemental Figure 1S).

6. The gantry is located on the cranial side of the patient and all cables (Bovie, suction and electromyography (EMG) monitoring, etc.) is let through the gantry (Figure 1B).

7. While the iCT-scanner is running, the surgical staff leaves the room, and thus avoid unnecessary radiation exposure (Figure 1C).

**Workflow for lumbar/lower thoracic spinal surgery with pedicle screw instrumentation:**

1. For lumbar/lower thoracic cases, a 2-pin fixator is attached to the patient’s pelvis using two 3mm Schanz pins. The RA is connected to the 2-pin fixator and tightened (Figure 2 and Supplemental Video).

2. For identification of the index level, the RA is attached to the iliac crest with the patient secured safely to the table (Figure 2). The RA may also be clamped to the spinous process (one or two levels cranially or caudally to the index level).

3. For the preoperative scan, two half sheets are draped around the incision site and the region of interest was marked on the drape (Supplemental Video).

4. An infrared camera is positioned towards the RA and the reflective markers on the gantry.

5. All personnel leave the OR before a radiology technician initializes the scan via a remote control. This eliminates the X-ray exposure for the surgical staff.

6. After the scan, the images are automatically transferred to the NAV.

7. The site of incision and its proper trajectory are identified with a pointer. In open cases, accuracy is confirmed by palpation of anatomical landmarks (i.e. spinous transverse process at several levels). In MISS, the tip of a transverse process is used to verify accuracy (Supplemental Video).

8. For MISS cases, a drill guide tube is calibrated and connected above the desired entry point through a small skin and fascial incision (Figure 3A-B) (10). The use of a navigated guide tube streamlines the workflow by eliminating K-wires and the need to navigate multiple instruments (Point-Drill-Tap-Screw) (11). The navigated guide tube is used for drilling, tapping, and screw placement (10) (Supplemental Video).
9. A power drill with a 3.2mm fluted drill bit was then used to prepare the entry point, followed by tapping the pedicle (Figure 3B) (10).

11. The desired screw is now inserted through the navigated guide tube. The screw is then stimulated; we use at threshold above 9 mA for acceptance of the screw position.

12. In cases where the case requires additional decompression and placement of a cage the following steps are followed: Bone graft can be harvested from the iliac crest and the pointer can be used for best localization of appropriate iliac crest bone. In cases where a tubular retractor is placed for decompression and facetectomy the fascial incision for the tubular retractor is determined with navigation. The fascial incision is typically 2 to 3 cm medially to the fascial incision required for screw placement. The pointer identifies the inferior edge of the lamina and the facet joint. Over a series of tubular dilators, the retractor is then placed and adequate exposure of the anatomy is again confirmed with the navigated pointer. The decompression and facetectomy is performed under the microscope and can also be done with the assistance of navigation. Navigation at this point will also be helpful to determine, for example, the localization of the pedicle, the disk space and the trajectory of the disk space. We then use navigation also to determine the trajectory of the discectomy and cage placement.

13. After placement of the cage a control CT scan is obtained. Based on this CT scan the length of the rods can be determined either with navigation or directly off the computer screen.

Workflow for localization of spinal pathology:

This is useful for spine tumors and cervical instrumentation cases please refer to our supplemental digital content.

1. The patient is placed either prone or supine and secured to the table using cloth tape as described in the lumbar total navigation workflow.

2. The RA is placed and secured either to the table or to a Mayfield head-holder depending on the anatomical region of interest (Figure 2).

3. For the preoperative scan, two half sheets are draped around the incision site and the region of interest was marked on the drape (Supplemental Video).

4. An infrared camera is positioned towards the RA and the reflective markers on the gantry.

5. All personnel left the OR before a radiology technician initialized the scan via a remote control. This eliminated the X-ray exposure for the surgical staff.
6. After the scan, the images are automatically transferred to the NAV.

7. The site of incision and its proper trajectory are identified with a pointer. In open cases, accuracy could be confirmed by palpation of anatomical landmarks (i.e. spinous transverse process at several levels). In MISS, the tip of a transverse process is used to verify accuracy (Supplemental Video).

8. Displacement of anatomical structures must be taken into consideration and re-scanning or anatomical landmark confirmation may be necessary especially treating intra-dural spine tumors.

9. A final CT is obtained in those cases where permanent hardware is implanted specially in occipito-cervical instrumentations (Supplemental Video)

Radiographic and clinical assessment

iCT screw accuracy was measured by independent review by evaluation of the immediate pre- and postoperative iCT scans according to Costa et al. (11). Accuracy of iCT-guided NAV was assessed by summing the screw grades (graded as 0 or 1) according to Laine et al. (12).

Radiation dose assessment

The radiation exposure received by the patient was assessed by extracting the amount of radiation from the NAV system.
Results

Baseline characteristics

iCT NAV has been successfully employed in 117 cases (115 patients), without complications (mean age: 62.5 ± 15.4 years; 57% female and 43% male) as illustrated in Table 1. Major indications included degenerative disease (65%), trauma (3.4%), neoplasm (8.5%), deformity (6%), and adjacent segment disease (10.2%). 69% of spine surgeries addressed the lumbar spine, whereas 21% addressed the cervical spine, and 10% addressed the thoracic spine (Table 1).

Utilization of iCT

iCT-guided NAV was utilized for the measurement of instrumentation (screws, rod and cage size), localization (incision planning, tubular retractor placement, extent of laminectomy, index level, spinal tumor, thoracic disc herniation), and assessment of neural decompression in ELIF and TLIF. Within all cases involving instrumentation, a second intraoperative scan was conducted to verify the implant position.

Radiation exposure

Our standard protocol included a preoperative and postoperative scan before wound closure. In the first two surgeries more than 2 scans per patient were required; hereafter, the mean number of scans per patient was 2.1. The effective dose per scan for normal, overweight, and obese patients was 5.5, 6.5, and 7.4 mSv respectively, with a mean dose of 13.4 mSv as shown in Table 1 (4).

Pedicle screw accuracy

The average time from “pointing” (pedicle identification through the navigated guide tube) to pedicle screw stimulation was 3.1 minutes. 390 pedicle screws (41 patients) were inserted in the lower cervical, thoracic and lumbar-sacral spine. 25 screws (6.4%) were identified with minor perforations (≤2mm), and four screws (1.0%) were misplaced with perforations (>2-4mm) (Table 1). Misplacement of >4 mm was not detected. As there is no clinical or structural difference between screws with a cortical violation (≤2mm) and screws without perforation (11), the accuracy of the iCT NAV was assessed by the number of screws evaluated as “misplaced” (12). All of the
cortical breaches were lateral. One malpositioned screw (1/390, 0.3%) was replaced after the second scan during the same surgery. No patient required a revision after leaving the OR.
Discussion

Over the past years, we have expanded the utilization of iCT NAV in order to make MISS safer, eliminate radiation exposure to the surgical staff and create more efficient workflows (Table 2). Here we summarize our initial experiences with total navigation in spine surgery (6).

Utility of iCT NAV

Total navigation can be applied in daily practice for various spinal procedures (Table 3). Specifically, in MISS, iCT-guided NAV is helpful in anatomic regions where conventional imaging techniques fail (i.e. cervico-thoracic junction), and therefore helps to eliminate, for example, wrong-level surgeries. Although wrong level surgery is a rare adverse event it nevertheless may have devastating consequences for the patient as well as for the surgeon (13). Data of The Joint Commission between 2004 and 2012 propose, wrong-site, or wrong-procedure events to be the most common sentinel events, accounting for 928 of 6994 events (13.3%) (14). Wrong-level and/or wrong site surgery still occur occasionally, especially when the anatomy is altered in severely degenerative cases, revision surgeries, spinal deformity, and/or variant vertebral morphology. In a recent report, 50% of spine surgeons stated that they have performed at least one or more wrong-level operation throughout their careers; in general, numbers for wrong-level lumbar surgery range from 0.04% to 5.3% (15-21). Furthermore, accurate radiographic identification of the index level can be challenging even for highly experienced surgeons. Misinterpretation of conventional intraoperative radiographs and subsequent failure in localization have been found to be a risk factor for wrong-level spine surgery (18, 22, 23). The portable system described here significantly supports localization of the index region. Additionally, iCT NAV can be used in multiple ORs, which increases versatility and flexibility and provides better cost efficiency compared to cheaper alternatives although it requires a higher initial cost (24).

Another condition in which iCT NAV truly supports the implementation of MISS principles are spinal tumors. In the past, spinal tumor cases were traditionally approached via maximal access surgery in order to obtain best-possible visualization to achieve R0 resection (whenever possible) according to the Union for International Cancer Control. As MISS constantly progresses, spine surgeons increasingly rely on advanced image guided navigation. Spinal tumor resection in a minimally invasive manner requests the knowledge about the exact localization in situ. Therefore, at our institution iCT NAV is used for precise localization of the pathology before tumor removal as well as subsequent planning of the skin incision in order to minimize soft tissue disruption, specifically in radiologically...
suggestive benign tumors and/or in the thoracic or cervico-thoracic transitional levels, where radiological orientation can be impaired by surrounding anatomical structures i.e shoulders (i.e. Schwannoma, Supplementary Case 1). Furthermore, utilization of the iCT NAV provides the opportunity to evaluate the resection / decompression immediately after tumor resection, especially due to the relatively high soft tissue resolution the iCT is able to provide. Though, a second scan is necessary due to the interventional anatomical alteration due to tumor removal.

**Effect of iCT on screw accuracy**

Use of iCT NAV and alternative technologies has demonstrated significant improvements in pedicle screw placement accuracy, as well as reduced complication risks and fewer reoperations (7, 25-34). Noriega et al. showed a reduction in the number of malpositioned screws from 10.3% to 3.6% when using iCT NAV instead of fluoroscopy (30, 35).

In the present study, we achieved an accuracy of 99% (5, 36-39). Our average time for screw placement was 3.1 minutes (from pedicle identification to position confirmation), which was shorter than in the literature (40-42). In summary, iCT-guided NAV for pedicle screw placement provides superior accuracy compared to conventional techniques, and reduces the risk of malposition (43-45).

**Total Navigation in MISS**

Total navigation in MISS has become feasible with the implementation of navigation guide tubes, resulting in the elimination of K-wires for screw placement (8, 9). At our institution, MIS-TLIF cases are now routinely performed with total navigation, and 75% of all cases are conducted using total navigation. iCT NAV provides the opportunity to immediately assess the surgical outcome intraoperatively. The authors of the present study and others corroborate that iCT-guided NAV enhances the accuracy and safety of spinal procedures and improves surgical workflow, especially in complex cases (4). For example, Sembrano et al. assessed neural decompression by an intraoperative CT myelogram (34). The iCT was able to intraoperatively detect inadequate decompression, suboptimal pedicle screw position, suboptimal interbody spacer position and malposition of a kyphoplasty trocar. Compared to the iCT used by Santos et al., the iCT used in the present study has a higher image quality (especially in terms of soft tissue). iCT NAV provides immediate feedback, thus allowing for repositioning of implants while the patient is still under anesthesia which helps to prevent reoperations, morbidity and additional expenditures.
Total navigation and radiation exposure

As illustrated in Table 1, the mean number of iCT scans was 2.1±0.76 per surgery resulting in a mean radiation exposure of 13.44 mSv. iCT-guided spine surgery was able to reduce radiation exposure received by both the surgical staff and the patient when compared to conventional fluoroscopy (46, 47). The need for fluoroscopy was eliminated in 75% of the cases presented in this study, which was in line with previous reports (5). Employment of total navigation allowed the entire OR staff to avoid radiation exposure as the iCT could be activated remotely, and wearing lead-shielded vests during surgery was no longer necessary (48, 49). Patient radiation exposure was dependent on whether full soft tissue capacity resolution was required or not. In the present work, usually 50% iCT intensity was used. Our standard protocol included a second postoperative iCT scan in order to verify implant position, sufficient decompression, screw size etc. before wound closure. As with all new techniques, becoming comfortable with iCT NAV requires practice and high frequency (50, 51). Previous studies and our results display that with time and practice, obtaining successful results with fewer CT scans was feasible (4). Many authors did not perform more than one iCT, which reduced OR time accordingly (4). In the present study, intraoperative radiation exposure for patients was lower than in other studies, but still higher than conventional fluoroscopy in some cases; however, varying results have been reported including some with contradictory data (i.e. Dabaghi et al.: 1.48±1.66 mSv (CT) vs. 0.34±0.36 mSv (C-arm) (P=0.0012); Smith et al.: 4.33 ± 2.66 mRem (fluoroscopy) vs. 0.33 ± 0.82 mRem (computer-assisted image guidance); (P = 0.012), (42, 52-55)).

Total navigation and workflow

Several authors have described a learning curve in using iCT NAV (4, 50, 51). However, the time investment required to gain sufficient experience with NAV may be ameliorated over time. Hecht et al. outlined an additional time for setup and navigation between 30 and 50 minutes with an additional surgical time of 18 to 34 minutes for their first three surgeries. For the following 20 procedures, less time was needed, which was in line with previous reports (5, 56). We believe that it takes practice to become proficient and efficient in using this new technology, and agree with previous reports which propose that a routine use of spinal navigation is critical to establishing a routine workflow (5, 50, 51, 56, 57). For this reason, we want to share our 8 step surgical workflow for total navigation (Table 4 and Supplemental Video).
Limitations, pitfalls and common errors

The present work contains experiences from a single-institution of highly dedicated staff, which may positively bias accuracy. Additionally, the initial accuracy of a surgeon with less experience using iCT NAV might be lower than reported here. Similarly, a less experienced user may require a higher number of scans when implementing total navigation due to re-calibration of the RA, which might lead to increased radiation exposure to patients. When performing benign tumor cases as demonstrated in the supplementary, a second scan is necessary due to the interventional anatomical shift after tumor removal. For novice operators, ensuring that all mandatory equipment is in order before the operation begins is suggested to avoid unnecessary time consumption. A list of required equipment can be found in Table 5.

iCT NAV presents its own limitations due to technical complications. However, inaccuracies detected from the tracking system were usually due to bloodstains on the reflective markers, which could easily have been corrected but would have required additional time. Also, the instrument attachments and navigation markers may have become loose during surgery and required retightening or re-calibration. Use of hammer or mallet can also cause some shift we recommend to use a navigated guide-tube and a power-drill instead. However, the iCT scan did not have to be repeated unless the RA attached to the spine had loosened. Furthermore, soft tissue movements as well as instrumentation at a large distance from the tracking device may have caused inaccuracy. Increasing the distance from the RA may also have contributed to reduced accuracy.

Finally, the iCT NAV was higher in initial cost than conventional NAV systems, and The iCT NAV is associated with costs which are currently not considered in the reimbursement (58). Despite the huge advancement of iCT-guided navigation, a careful and repeated control of accuracy during all steps of surgery is mandatory. Utilizing easy accessible anatomic points to verify a proper registration and function of the system is highly recommended (59). Whenever in doubt, fluoroscopy should be used to verify correct anatomical position as it can be easily integrated at any time during the surgery.
Future perspectives

As long as patient radiation can be maintained within the safety limits, total navigation should be further implemented and developed. Although clinical benefits are not obvious during the short-term postoperative period, we believe that long term studies will further elucidate the huge benefits of iCT-guided NAV. Total navigation using iCT NAV is relatively easy to learn and makes spine surgery, especially MISS, safer and more efficient. Total navigation ensures frequent and routine utilization of image-guidance, which facilitates and optimizes the workflow and potentially leads to improved clinical and radiologic outcome. Total navigation does not substitute surgical experience, skill or knowledge, but can improve on the training of young surgeons by allowing rapid feedback at all steps during surgery. The advancement of MISS techniques that aim to further reduce approach-related morbidity will be dependent on accurate 3D visualization. Finally, as radiation exposure remains a major concern for the patient and surgical staff, minimization or elimination of radiation should be attained whenever possible. Future research must further describe the cost-benefit-ratio of iCT NAV, especially the implications of clinical outcome, complications (i.e. wrong level surgery), and reoperation rates as well as the potential combination with robotic surgery.

Conclusions

In conclusion, the latest generation of mobile iCT expands the role of navigation from a tool that was only used for placement of screws to a technology that is now used throughout the entire procedure. Using iCT NAV in conjunction with navigated guide tubes eliminates the need for fluoroscopy in 75% of cases and optimizes outcomes in spinal surgery (40). We predict that going forward, navigation will increasingly replace fluoroscopy in spinal surgery.
Declaration of interest

The authors declare that they have no conflict of interest.

Roger Härtl, M.D. has the following financial disclosures:

Consulting fees: AO Spine, Brainlab, DePuy-Synthes and Lanx

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Beside Roger Härtl and Gernot Lang, the other authors have nothing to disclose.

The authors of this manuscript declare that there is no conflict of interest.

Ethical standards

The study was approved by our local institutional review board and informed consent was obtained from all patients before surgery. All human studies have been performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

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Figure captions

Figure 1. iCT OR Setup

From left to right: A) Before surgery, the iCT is parallel with the rail system. B) Intraoperative OR suite setup. The patient is face-down with arms up for a lumbar procedure (note: arms should be placed down at the side for cervical surgery). It is important to lead all anesthesia, EMG, Bovie, and suction cords through the gantry of the iCT. Cloth tape is applied across the chest and hips and laterally from the patient’s side downwards in order to minimize tissue movement and shifting during surgery. C) OR suite setup when taking iCT scans of the patient. All personnel leave the room while the iCT is in use.

Figure 2. Reference array

A) For pathology of T12-pelvic, the reference array (RA) is placed in posterior iliac crest via a 2-pin fixator (lower right) B. For pathology of C3-T11, the RA is placed on a spinous process (mid right) C. For pathology of C0-C3, the RA is docked in the Mayfield head clamp (top right) D. For localization only (i.e. intraraquideal tumor, thoracic disc herniation etc.) from occiput to pelvic, the RA is attached to the table with the patient adequately immobilized with tape (not shown).

Figure 3. Total navigation workflow (8 step guide)

From top to bottom and left to right. A) Skin incision is planned with the pointer. B) Screw trajectory planning and power-drill tap. C) “Hands-off” test for screw placement controlled via screen display. D) Tubular retractor placement E) Microsurgical decompression. F) Cage size prediction is performed and controlled under image guidance. E) Rod length is measured by image guidance. F) iCT scan is performed before wound closure to evaluate morphological outcome.
References


Table 1. Patient demographics of 115 patients undergoing spinal surgery (117 cases)

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</tr>
<tr>
<td>Number of Cases</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Number of Screws</td>
<td>309</td>
<td></td>
</tr>
<tr>
<td>Time per screw in minutes</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Minor Breach &lt; 2mm</td>
<td>25</td>
<td>6.4</td>
</tr>
<tr>
<td>Misplaced &gt; 2-4mm</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Misplaced &gt; 4mm</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

N: absolute number; %: relative number in percent; IONM: Intraoperative neurophysiologic monitoring; iCT: intraoperative CT; SD: standard deviation; MISS: Minimally invasive spine surgery
Table 2. Tips to improve accuracy in iCT-guided navigation

| Draping                                                                 | • Securing the patient with tape to the OR table minimizes tissue movement  
|                                                                      | • Tape across the chest and hips and laterally from the patient’s side downwards  
| Intraoperative scan                                                   | • Include anatomical landmarks allowing accurate determination of the index level /pathology.  
|                                                                      | • Obtain introp CT immediately before it is actually needed (some times after the anatomical structures have been exposed e.g. posterior cervical cases, this minimizes the chances of shift and inaccuracies caused by surgical manipulation  
| Verification of accuracy                                              | • Point out the tip of the transverse process after skin incision (in MISS)  
|                                                                      | • Constantly compare position and tactile feedback of the navigated instrument during surgery  
|                                                                      | • Reflective markers should not be contaminated  
| Throughout the procedure                                             | • Confirm stable placement and avoid hitting the array during surgery  
|                                                                      | • Avoid pressure, mechanical impact (with hammers or mallet) or movements  
|                                                                      | • Use a battery driven drill to prepare screw holes and avoid Jamshidi needles  
| “Hands-off test”                                                      | • After full insertion of the tap into the pedicle, let go of the instrument  
|                                                                      | • If the screw simulation on the navigation screen demonstrates an adequately positioned screw in the pedicle without breach, this is usually a confirmation of a well-placed screw trajectory (not in osteoporotic patients)  
| Neuromonitoring                                                      | • Intraoperative neuromonitoring and screw stimulation with a cut-off of approximately 9 mAmp  
| Verification of position                                             | • iCT scan after implantation of instrumentation / implants to verify desired position and accuracy  

Table 3. Utilization of iCT-guided navigation for the most common spinal procedures

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Position</th>
<th>Reference Array</th>
<th>Additional Fluoroscopy</th>
<th>TOTAL NAVIGATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Incision</td>
</tr>
<tr>
<td>CERVICAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O-C fusion*</td>
<td>Prone</td>
<td>Mayfield HH</td>
<td>☐</td>
<td>YES</td>
</tr>
<tr>
<td>Anterior cervical corpectomy</td>
<td>Supine</td>
<td>Mayfield HH</td>
<td>☐</td>
<td>YES</td>
</tr>
<tr>
<td>Posterior/cervico-thoracic instrumentation C2-T10</td>
<td>Prone</td>
<td>Spinous process</td>
<td>☐</td>
<td>YES</td>
</tr>
<tr>
<td>THORACIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoracic Tumor Removal</td>
<td>Prone / lateral</td>
<td>Spine process/Table</td>
<td>☐</td>
<td>YES</td>
</tr>
<tr>
<td>Thoracic Discectomy</td>
<td>Prone / lateral</td>
<td>Spine process/Iliac Crest (lat. Approach)</td>
<td>☐</td>
<td>YES</td>
</tr>
<tr>
<td>LUMBAR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct repair of pars defect</td>
<td>Prone</td>
<td>Iliac Crest</td>
<td>☐</td>
<td>YES</td>
</tr>
<tr>
<td>Far lateral discectomy</td>
<td>Prone</td>
<td>Iliac Crest/Table</td>
<td>☐</td>
<td>YES</td>
</tr>
<tr>
<td>MIS-TLIF</td>
<td>Prone</td>
<td>Iliac Crest</td>
<td>☐</td>
<td>YES</td>
</tr>
<tr>
<td>ELIF± Posterior Decompression/Fusion</td>
<td>Lateral</td>
<td>Iliac Crest</td>
<td>☐</td>
<td>NO</td>
</tr>
</tbody>
</table>

☐ Absence, ☑ Presence, O-C: occipito-cervical; HH: head holder, ELIF: Extreme Lateral Interbody Fusion; MISS: Minimally Invasive Spine Surgery; TLIF: Transforaminal interbody fusion, IONM: Intraoperative neurophysiologic monitoring; Decompress.: decompression; lat: lateral; * In general the CT is obtained immediately before needed, that means after anatomical exposure and before screw insertion.
Table 4. 8 step workflow for total navigation (Refer to Supplemental Digital Content).

<table>
<thead>
<tr>
<th>8 Step workflow for total navigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Supplemental Digital Content)</td>
</tr>
<tr>
<td>1. Skin incision planning</td>
</tr>
<tr>
<td>2. Screw size prediction</td>
</tr>
<tr>
<td>3. Screw placement (Point-Drill-Tap-Screw)</td>
</tr>
<tr>
<td>4. Tubular retractor placement</td>
</tr>
<tr>
<td>5. Decompression</td>
</tr>
<tr>
<td>6. Cage placement</td>
</tr>
<tr>
<td>7. Rod measurement</td>
</tr>
<tr>
<td>8. Final CT check</td>
</tr>
</tbody>
</table>
### Table 5. Equipment needed for total navigation

<table>
<thead>
<tr>
<th>Mandatory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intraoperative CT scanner</td>
</tr>
<tr>
<td>Infrared tracking camera navigation system</td>
</tr>
<tr>
<td>Image-guidance system (navigation unit)</td>
</tr>
<tr>
<td>Patient reference array + 2-pin fixator (or spinous process clamp)</td>
</tr>
<tr>
<td>Navigated pointer</td>
</tr>
<tr>
<td>Navigated guide tube (Power Drill, Tap, Headless screws)</td>
</tr>
<tr>
<td>Microscope or surgical loupes</td>
</tr>
<tr>
<td>EMG monitoring</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mayfield head clamp (cervical)</td>
</tr>
</tbody>
</table>
Highlights

- We introduce a concept of “total” navigation in spine surgery
- We are able to incorporate the use of total navigation into our daily practice and eliminate the use of fluoroscopy in ~70% of our spine cases
- We can decrease to 0 the radiation exposure for the surgical staff in ~70% of our spine cases
- Modifications to our concise and step by step technique can be applied to replicate our workflow in other sites around the world
Abbreviations

ELIF: Extreme Lateral Interbody Fusion

EMG: Electromyography

iCT NAV: Intraoperative Computer Tomography Navigation

MIS-TLIF: Minimally Invasive – Trans Foraminal Interbody Fusion

MISS: Minimally Invasive Spine Surgery

NAV: Image Guided Navigation

OR: Operating/Operating Room

RA: Reference Array