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Review

Computer tomography-assisted 3-dimensional navigation in spine surgery: a narrative review on safety, accuracy, efficacy and reduction of complications

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Abstract

The computed tomography-assisted 3D navigation system is a useful tool for spinal surgeons, enabling them to enhance the effectiveness and safety of surgical procedures by providing real-time three-dimensional information during decompression, resection, and instrumentation. Specific advantages of this navigation system include precise pedicle screw placement, the capability for immediate intraoperative correction, and execution of minimally invasive surgeries with reduced radiation exposure for the surgical team. Noteworthy disadvantages of this system are the relatively high implementation costs, the need for specific training, and limited accessibility to outpatient surgery centers. Currently, spinal navigation systems are constantly being upgraded with additional innovations, such as integration with robotics and improvement of the existing tools, which will ultimately lead to a better quality of life for patients and an improved experience for surgeons.

Keywords

navigation, O-arm, robotic-assisted surgery, screw placement, spine, surgery

Introduction

In recent decades, spinal fusion of two or more segments in various spinal diseases, such as degenerative diseases, scoliosis, trauma, tumors, and infections, is often performed by a wide range of instrumentation systems. Misplacement of pedicle screws can lead to neurological, vascular, or visceral injuries, hardware malfunction, and an increase in medical costs.[1,2] The identification of screws that have been placed incorrectly necessitates their repositioning, a process that invariably prolongs the surgical procedure, which, in its turn, increases the exposure of the patient and the surgical team to radiation while inflicting additional tissue trauma and blood loss.[3] In cases of postoperative neurovascular complications, revision surgery is often mandatory, thereby increasing medical costs and morbidity. Current literature reports screw misplacement rates ranging from 5% to 41% for the lumbar and 3% to 55% for the thoracic spine, highlighting the need to improve the accuracy of pedicle screw placement.[4] In an effort to mitigate these risks and complications, surgeons frequently employ navigation systems to ensure safe and effective surgical procedures.[1]

Currently, techniques for placing pedicle screws include the “free-hand”, fluoroscopy-assisted, computer tomography-assisted 3D navigation (CT3DN), and robotic navigation techniques.[1] In the “free-hand” and fluoroscopy-assisted techniques, surgeons use specific anatomical landmarks to determine the entry point for screw placement and trajectory guidance. This carries the risk of improper screw placement, especially in the high and mid thoracic spine, severe spinal deformities, or in the scenario of significant pedicle anatomy variations. This fact justified the need for the development of CT-based navigation systems, resulting in faster and more precise procedures.[5] In order to evaluate the qualities and advantages of a specific navigation system, it is necessary to compare intraoperative and postoperative clinical outcomes, the accuracy of pedicle screw placement, and potential complications between navigated and conventional techniques.

Efficacy and safety of pedicle screw placement with spinal navigation

A number of studies report improved accuracy and safety of pedicle screw placement when using intraoperative CT3DN compared to fluoroscopy-assisted techniques.[6-8] Other studies found no significant differences in accuracy between these two approaches.[9,10]

Amiot et al. reported 15.3% error rate for 544 screws placed in the T5-to-S1 segment using the free-hand technique, compared to only 5.4% for 295 screws placed when using CT3DN.[11] When evaluating 2062 thoracic and lumbar pedicle screws using intraoperative CT-assisted navigation, Yu et al. found that only 4.6% of screws breached the pedicles by more than 2 mm, compared to a 16% rate of misplacement using the free-hand technique.[12] Of 1288 placed pedicle screws (665 with C-arm and 643 with O-arm), Cammarata et al. reported correct placement in 92.8% in the C-arm group and 98.1% in the CT3DN group.[13] Medial breach of the pedicle cortex was found in 13 screws (Grade B, 1.95%), 19 screws (Grade C, 2.86%), 14 screws (Grade D, 2.11%), and two screws (Grade E, 0.3%) in the C-arm group, whereas in the CT3DN group, 11 screws were Grade B (1.71%) and only one was Grade C (0.16%) according to the Gertzbein and Robbins classification.[13,14]

Heath et al. performed minimally invasive pedicle screw fixation in 100 patients with 514 screws, using CT3DN for 52 patients and robotic-assisted navigation for the remaining 48. Perfect accuracy (Grade A) was achieved in 98% of the robotic-assisted navigation group and 80% in the CT3DN group. Clinically satisfactory accuracy (Grade A and B) was achieved in 100% of the robotic group and 92.2% of the CT3DN group, with no revision surgeries needed in either group for misplacement.[14] Incorrectly positioned screws (Grade C and D) were not found in the robotic-assisted group, while they occurred in 7.8% of the CT3DN group.[14]

A meta-analysis of 30 studies by Papalia et al., involving 17,911 patients and 24,600 pedicle screws, found statistically significant accuracy improvements with navigation systems compared to traditional techniques (96.2% vs. 94.2%).[1] Similar results were found in previous meta-analyses and publications.[5,15]

Perdomo-Pantoja et al.’s systematic review and meta-analysis of 51,161 pedicle screws reported 95.5% correct screw placement with CT3DN, compared to 93.1% with fluoroscopy-assisted navigation and 91.5% with the free-hand technique, respectively.[16]

A key advantage of intraoperative CT3DN navigation is its ability to correctly determine the screw-to-pedicle diameter ratio in real time, allowing for the placement of an optimally sized screw, thus increasing the stability and strength of the construct.[17]

Influence of the usage of CT3DN on clinical symptoms

Improving patient outcomes and reducing complication rates are crucial factors in spinal surgery, especially when evaluating the costs and learning curves of new systems and workflows.[18] Studies by Chen et al. and Singhatanadgige et al. using the visual analog scale (VAS) showed superior improvement in leg and back pain with the use of CT3D navigation compared to fluoroscopy-assisted techniques, although without statistical significance.[19,20]

Comparison of intraoperative and postoperative revision rate of pedicle screws

According to studies by Wang et al. and Chatelain et al., the rate of intraoperative revisions of pedicle screws is similar between CT3DN and conventional techniques, while the rate of postoperative revisions is significantly lower in CT3DN surgeries due to the opportunity for simultaneous intraoperative screw placement correction.[15,21]

Comparison of intraoperative radiation exposure

All navigation systems are associated with radiation exposure of the patient and the surgical team. While patient exposure occurs only during the specific surgical intervention, frequent exposure to such radiation for the surgical team can lead to significant accumulated doses over time. The widespread use of modern navigation systems in spinal surgery is undeniably potentiated by the risk for significant radiation exposure while using conventional techniques.

In 2008, a study by Smith et al. showed that CT3DN reduces the average radiation dose compared to conventional fluoroscopy from 433±266 mGy to 33±82 mGy.[22] Theocharopoulos et al. demonstrated that the radiation exposure of spinal surgeons is 50 times greater than the lifetime radiation dose of hip surgeons, highlighting the need to limit radiation exposure.[23] Many studies report a reduction in radiation exposure when using CT3DN compared to fluoroscopy-assisted procedures.[24,25] Gebhard et al. noted that the average absorbed dose when using C-arm navigation is 1,091 mGy, compared to 664 mGy with virtual fluoroscopy, 432 mGy with CT-based fluoroscopic navigation, and 152 mGy with CT3DN.[24] Radiation exposure for the surgeon in minimally invasive spinal interventions exceeds the permitted dose of professional exposure after 194 interventions.[26]

All studies support the view that new technology for intraoperative imaging is necessary to make spinal surgery safer. Reducing the radiation exposure is one of the key advantages of CT3DN. According to Kim et al.[27], the fluoroscopy time is reduced by 90 seconds, and additionally, it can protect the surgeon from radiation exposure as it allows them to leave the operating room during intraoperative scanning. Nottmeier et al.[28] showed in their study that the exposure of the surgical team was minimal if they were at least 10 steps away from the device.

Besides reducing radiation exposure of the surgical team, navigation can also reduce the exposure of the patient.[25] In a series of 40 patients who underwent posterior instrumentation, Kraus et al. found an average effective dose of 0.4 mGy in the group with intraoperative computer-assisted navigation, compared to 5.03 mGy in the fluoroscopy group.[25]

Comparison of operative times

A significant number of recent studies demonstrate that the operative time is shorter when using conventional techniques, although the differences are not statistically significant.[19,29-31] Papalia et al. explain this result by the additional time required to obtain CT images, calibrate intraoperative navigation instruments, or the learning curve of surgeons.[1] A meta-analysis by Meng et al.[32] showed that the operative time with CT3DN was significantly longer, while the time for placing pedicle screws in the thoracic region was shorter compared to fluoroscopy-assisted navigation.

Comparison of blood loss and hospital stay

It has been established that blood loss and hospital stay are significantly lower when using CT3DN compared to conventional techniques.[20,21,29,33-35] These results are largely attributed to the increasing use of minimally invasive spinal surgery (MISS), performed with the help of navigation systems that allow access to the pedicles of the vertebrae with less soft tissue damage, less blood loss, and therefore shorter hospital stays.[36,37]

The role of spinal navigation in minimally invasive spine surgery

Minimally invasive spine surgeries use a percutaneous approach, and in these cases, tactile and visual orientation are not possible.[38] This significantly increases the need for CT3DN to visualize the bone anatomy of the pedicles and vertebral bodies for correct pedicle screw placement. A MISS does not allow the use of point-pair registration required for preoperative CT-based stereotaxy, as the bone landmarks necessary for registration are not exposed in the surgical field. For these reasons, the latest image-guided surgical systems, such as intraoperative CT3DN, are used worldwide. These systems improved registration accuracy, enabling reliable real-time feedback regarding the relative positions of the instruments within the 3D map provided by intraoperative imaging.[39] Such accuracy and reliability of computer-provided anatomy are of great importance in cases of limited exposure, such as in MISS. Bourgeois et al. found that from 2,132 percutaneous pedicle screws implanted by means of CT3DN, the rate of misplacement was only 0.33%.[40]

Virk and Qureshi highlight the advantages of navigation in MISS, especially in complex spinal anatomy, such as in the C1-C2 area.[41] The ability of navigation to provide accurate real-time feedback depends on reference markers, which may vary among different systems. These markers are usually attached to anatomical structures within the surgical field. It is essential to prevent any movement of the attached trackers after the scanning is completed to maintain the reliability of the navigation accuracy. However, this can be challenging due to limited exposure and relatively bulky reference markers.[42] A skin-based marker system, used for minimally invasive transforaminal lumbar interbody fusion, was proposed by Vaishnav et al. as a way to prevent overcrowding of the surgical field.[42] This less bulky registration system can successfully be used in procedures involving smaller skin incisions. Another study showed both significantly shorter operative time (on average 92 minutes vs. 108 minutes) and less blood loss (on average 25 mL vs. 50 mL), as well as a 29% reduction in the average radiation dose for the patient compared to the fluoroscopy group.[43]

Comparison of complications

A systematic review and meta-analysis by Papalia et al. found significantly fewer systemic and neurological complications in patients operated on with CT3DN compared to those using conventional techniques (118 vs. 825 and 20 vs. 35, respectively).[1]

Cost-effectiveness of spinal navigation systems

Healthcare in most countries is oriented toward the most cost-effective systems, therefore until recently, the costs of modern navigation systems were considered unfeasible. Gradually, studies demonstrated a significantly reduced number of revision surgeries when using CT3DN, which led to acceptance of its use.[39]

The analysis by Al-Khouja et al. showed that the costs of CT-based navigation range from $8,820.51 to $9,188.87 per surgery, while the costs for revision surgery range from $17,650 to $39,643, illustrating the potential for substantial savings by avoiding revision surgery despite the higher initial investment in the CT-assisted navigation system.[44]

Conclusion

The CT-assisted 3D navigation system is an extremely useful tool that enables spinal surgeons to perform efficient and safe surgeries. This modern technology cannot replace the traditional anatomical and surgical competence, but it definitely improves the accuracy of instrumented procedures, allows for significant reduction in radiation exposure of the surgical staff, and reduces systemic and neurological complications. The CT-assisted 3D navigation system can even facilitate the resection of spinal column tumors and is particularly useful in MISS. Limitations to the widespread utilization of the CT-assisted 3D navigation system include the significant costs of purchase and the necessity for training the surgical team to easily overcome the learning curve. Currently, the efficacy, efficiency, and safety of navigation systems are proven, which fully justifies the costs, and this will encourage the widespread use of modern navigation techniques. Further randomized studies will be needed to definitively establish patient-specific variables such as intraoperative blood loss, complications, and postoperative clinical outcomes.

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