

The Integrated Operation Theatre Spine Suite in the Robotic Era: From a Collection of Technologies to a Surgical Ecosystem

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Abstract

Technological progress in spine surgery has moved beyond the introduction of individual devices. The more important challenge now is to make different enabling technologies interact in a deliberate, pathology-specific workflow. We propose a practical sequence for complex spine surgery: plan → visualize → navigate → execute → monitor → verify → integrate. Three-dimensional imaging and robotic planning can define anatomy and trajectories; three-dimensional digital visualization can improve the operative view and create a shared screen for the entire team; navigation can localize both implants and active instruments; robotic guidance and ultrasonic bone-cutting technology can assist execution; intraoperative neuromonitoring (IONM) can provide physiological feedback during critical manoeuvres; and intraoperative imaging can verify the result before closure. At our institution, this philosophy includes the complementary use of a Medtronic Mazor X robotic guidance platform, a ZEISS KINEVO robotic visualization platform, and third-party navigation registered to an ultrasonic bone scalpel handpiece. During procedures such as corpectomy, tracking the working tip can add spatial information as the cut approaches a less visible cortical boundary adjacent to critical neural or vascular structures. Navigation does not replace direct vision, anatomical knowledge, or surgical judgment; it adds another layer of information where the margin for error is small. Three-dimensional digital visualization also converts complex surgery into a shared teaching environment because the surgeon, assistant, fellows, nurses, and observers can view the same operative anatomy being projected on the screen by the exoscope using 3D glasses. The central philosophy is therefore simple: one system may help us reach the target, another may help us see the target, navigation may show where the working instrument lies, and IONM may show how the nervous system is responding. The surgeon integrates these inputs and remains the final decision-maker. The future is not the accumulation of technology, but the purposeful integration of technology around the patient and the operation.

Categories: Quality Improvement, Orthopedics, Neurosurgery

Keywords: complex spine surgery, enabling technology, exoscope, intraoperative neuromonitoring, navigation, robotics, spine surgery, three-dimensional imaging, ultrasonic bone scalpel

Editorial

From a technology-rich operating room to a technology-driven workflow

Modern spine surgery has access to an extraordinary range of enabling technologies: fluoroscopy, three-dimensional imaging, navigation, intraoperative neuromonitoring, endoscopy, advanced optical systems, ultrasonic bone-cutting devices, and robotics. Their individual value is well recognized. The next challenge is different. It is to decide how these technologies should be combined during the same operation so that information generated by one platform meaningfully changes the use of another.

In a previous guest editorial, we described the Integrated Operation Theatre Spine Suite (IOTSS) as a concept for bringing multiple enabling technologies together within a dedicated spine-surgery environment (Figure 1) [1].

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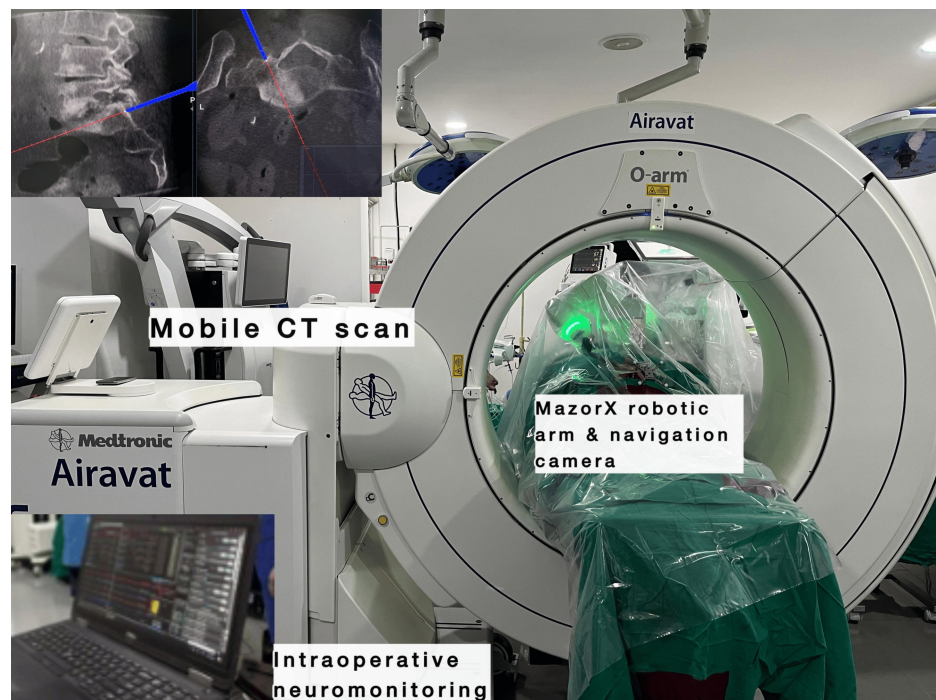


FIGURE 1: Integrated Operation Theatre Spine Suite

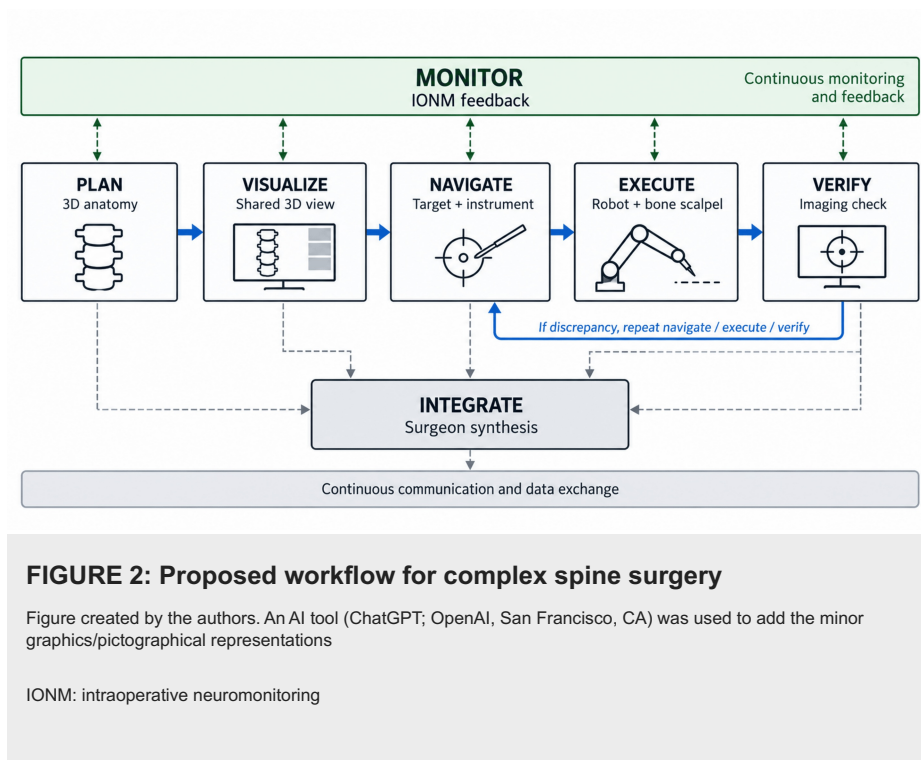
Written informed consent for publication of these images was obtained from the patient

This article does not repeat that historical or conceptual description. Instead, it proposes a new framework centered on workflow, especially for complex spine pathology. The emphasis is not on how many devices are present in the operating room, but on whether the surgeon can use them sequentially and interactively to improve planning, visualization, localization, execution, physiological surveillance, verification, and decision-making.

For complex surgery, technology should not function as a collection of isolated islands. The operation should become a connected sequence in which each step answers a different clinical question, and the surgeon integrates the answers.

An integrated workflow for complex spine pathology

For complex deformity, cervical reconstruction, tumour surgery, revision surgery, or anatomically demanding decompression, we propose an integrated workflow practised at our institute (Figure 2).



This sequence was developed by analysis of the functional sequence of technologies used during technology-enabled spine surgery. Individual technologies were categorized according to their principal operative function and organized into seven domains: planning, visualization, navigation, execution, monitoring, verification, and integration. The sequence is not rigid, and some steps may overlap or repeat during an operation. Its value is that it forces the team to define the purpose of each technology before it is used.

Planning asks: What is the pathology, what is the objective of surgery, and where are the danger zones? Visualization asks: What anatomy must be seen clearly and shared with the team? Navigation asks: Where is the target and where is the instrument in relation to that target? Execution asks: Which tool can perform the planned manoeuvre most precisely? Monitoring asks: How is the nervous system responding while we operate? Verification asks: Did we achieve the intended decompression, reconstruction, alignment, and implant position? Integration asks the most important question: What do all these sources of information mean for this patient at this moment?

Plan: define the operation before activating the technology

Technology should begin with a surgical question, not with a machine. The pathology and the patient's clinical problem must determine the indication, the approach, the extent of decompression or reconstruction, and the need for fixation. Once these are defined, three-dimensional imaging, preoperative planning, or robotic planning can be used to clarify anatomy, trajectories, implant dimensions, and potential areas of risk.

This distinction is important because an accurate robot can reproduce an inaccurate plan. Technology therefore cannot correct a poor indication or an inappropriate operative strategy. The first and most important step remains human judgment.

Visualize: seeing the target and sharing the operative field

Visualization is not merely magnification. In complex surgery, the surgeon needs illumination, depth perception, ergonomic freedom, and the ability to maintain orientation during long or technically demanding procedures. At our institution, a ZEISS KINEVO 900 robotic visualization platform is used in microscopic and exoscopic modes, depending on the surgical requirement. Three-dimensional digital visualization is feasible in spine surgery and may provide ergonomic and educational advantages [2].

Its teaching value is particularly important. Traditionally, the best view belonged to the operating surgeon. The assistant saw less, and observers often saw only fragments of the procedure. A three-dimensional digital screen changes this hierarchy. By using the three-dimensional glasses with the digital screen, the surgeon, assistant, fellows, nurses, and observers can see essentially the same anatomy at the same time with depth perception. The senior surgeon can identify a structure, demonstrate a manoeuvre, explain a danger zone, and correlate what is seen with navigation or imaging (Figure 3).



FIGURE 3: A senior surgeon demonstrating critical anatomy and surgical maneuvers on the Zeiss Kinevo 900 3D 4K exoscope

Written informed consent for publication of these images was obtained from the patient

The operating room therefore becomes not only a place of treatment, but also a live three-dimensional classroom.

Shared visualization also improves communication. When the entire team sees the same critical step, instructions become more precise, and the rationale behind a manoeuvre becomes easier to understand.

Navigate: from locating implants to locating the working instrument

Navigation in spine surgery is commonly associated with pedicle screw placement. That is valuable, but it is only one application. Large contemporary clinical experience demonstrates that robotic and navigated workflows can provide highly accurate thoracolumbar instrumentation [3]. The broader opportunity is to extend navigation from implants to the operation itself.

The relevant question is no longer only, 'Where should I put the screw?' It can also be, 'Where is the active tip of the instrument while I am removing bone?' This becomes particularly useful when the working end of an instrument approaches an anatomical boundary that cannot be continuously visualized.

At our institution, we use a flexible factory-calibrated mount that can be attached to a third-party instrument like the ultrasonic bone scalpel using a clamp. This third-party instrument can then be registered with the navigation system for a live virtual image during usage (Figure 4).

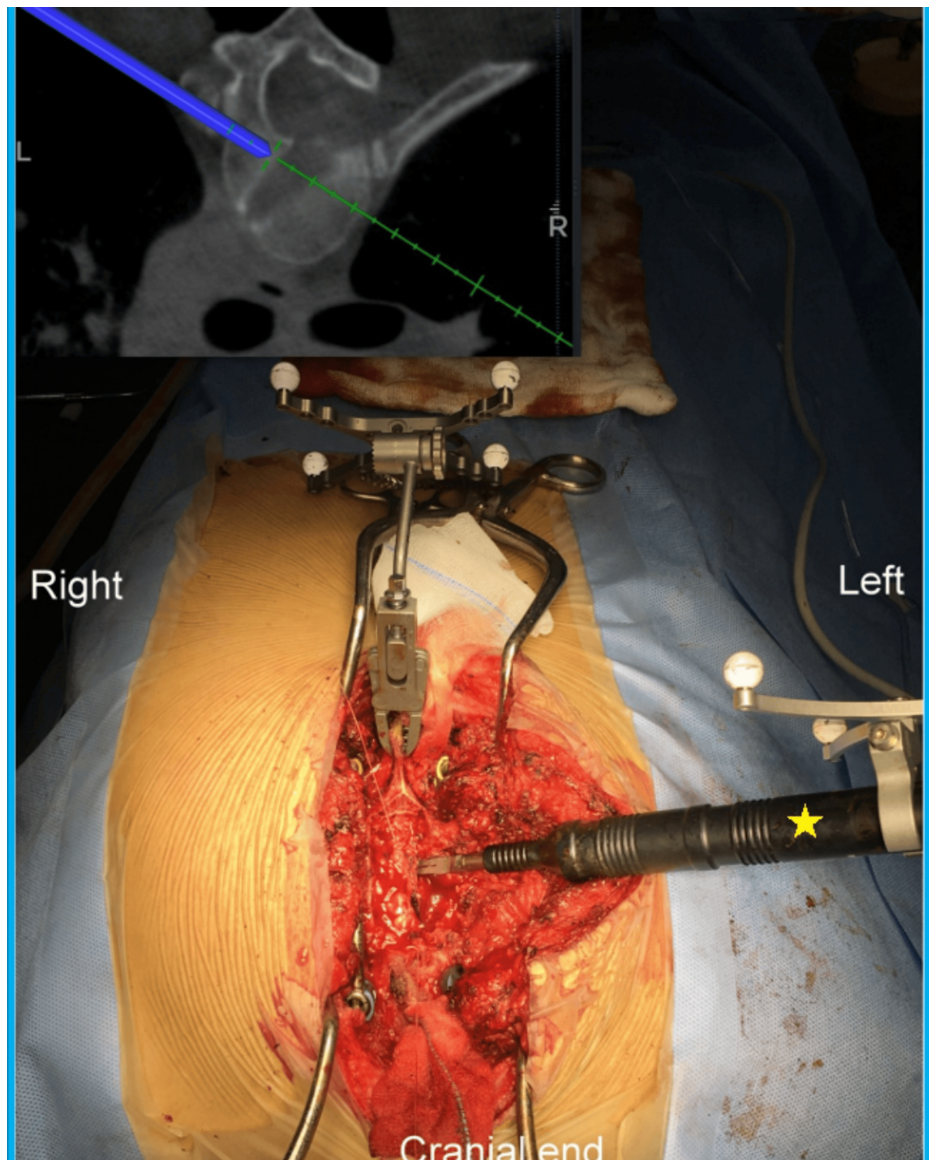


FIGURE 4: UBS mounted with a factory-calibrated navigation attachment (marked with yellow asterisk) being used to create trough space by cutting out a bone block in a 19 year-old patient with T3-4-5 progressive gibbus with myelopathy

The virtual image in the upper left corner showing navigated UBS is being used to cut out the bone block ventral to the cord and a thin slab. Written informed consent for publication of these images was obtained from the patient

UBS: ultrasonic bone scalpel

The working tip can then be displayed relative to the patient's reconstructed three-dimensional anatomy. The feasibility of image-guided registration of an ultrasonic bone scalpel for spinal bone resection has previously been described in tumour surgery [4]. The significance of the technique is not simply technical. It represents a conceptual shift from navigation of implants to navigation of active surgical work.

Execute: robotic guidance with controlled bone removal

Execution is the step at which planning, visualization, and navigation become action. Robotic guidance can help reproduce a planned trajectory of screws and reduce variability during instrumentation. Ultrasonic bone-cutting technology can assist controlled bone removal. These tools become more valuable when they are not used in isolation but are informed by the preceding steps of the workflow.

Cervical corpectomy provides a useful example. We have previously reported the utility of the ultrasonic

bone scalpel in cervical corpectomy [5]. Much of the vertebral body can be removed under direct visualization. However, as the cut approaches the posterior or lateral cortical boundary, the margin for error becomes smaller. Depending on the direction of the cut, the opposite side of the remaining cortex may be close to the spinal cord, nerve root, vertebral artery, or other critical structures. In addition to this, the use of navigated bone removal can be extended to thoracic kyphosis, where ventral sculpting of the kyphotic vertebral body can be utilized for targeted decompression [6].

When the bone-scalpel handpiece is tracked, the surgeon can look at the operative field while also following the position and orientation of the working tip on the navigation display. The cut can progress from the visible surface toward a less visible boundary while the spatial position of the tip is observed. As the planned depth or anatomical limit is approached, further advancement can be stopped.

Navigation as a virtual extension of vision

This integration should not be misunderstood as permission to perform blind cutting. Direct visualization remains fundamental. Navigation is an adjunct, and its accuracy depends on correct registration, stable reference arrays, calibration of the instrument, absence of unnoticed movement, and repeated confirmation that the displayed anatomy still corresponds to the patient.

The value is different: direct vision shows what is visible in the operative corridor, whereas navigation can add information about where the working tip lies in the wider three-dimensional anatomy. In this sense, navigation becomes a virtual extension of vision precisely at the point where the anatomy becomes less forgiving.

This is one of the clearest examples of true technological integration. The bone scalpel provides controlled cutting; navigation provides spatial localization; three-dimensional visualization provides the operative view; and the surgeon decides how far to proceed. One technology increases the usefulness of another.

Monitor: physiological information during critical manoeuvres

Anatomical precision alone is not enough in complex spine surgery. The spinal cord and nerve roots are functional structures, and intraoperative neuromonitoring provides a different type of information from imaging or navigation. While navigation answers an anatomical question, IONM can provide physiological feedback during deformity correction, decompression, instrumentation, tumour surgery, or other high-risk manoeuvres.

IONM should not be described as a guarantee of safety. Signals can change for technical, anaesthetic, systemic, or surgical reasons, and false-positive or false-negative information can occur. Its value lies in providing another layer of surveillance that can be interpreted together with what the surgeon sees, what navigation shows, what imaging demonstrates, and what manoeuvre has just been performed.

In an integrated workflow, a signal change is therefore not an isolated alarm. It becomes information that can trigger a structured response: stop the manoeuvre, reassess blood pressure and anaesthesia, review implant or instrument position, inspect the operative field, reverse a correction if appropriate, obtain imaging, and decide the next step.

Verify: close the loop before leaving the operating room: second intraoperative 3D CT

A technology-enabled operation should not end with execution. The result should be verified. Depending on the procedure, verification may include direct assessment of decompression, three-dimensional imaging, navigation-based confirmation, implant review, alignment assessment, or correlation with neuromonitoring and the final operative field.

Verification is particularly valuable in complex and revision surgery because distorted anatomy, long constructs, difficult exposure, or multiple critical steps increase the consequences of an unrecognized error. Intraoperative verification creates an opportunity to correct a problem while the patient is still in the operating room rather than discovering it later on postoperative imaging. Long film 2D and 3D intraoperative CT using O-arm scan gives the opportunity to correct or modify the procedure before wound closure.

Integrate: the surgeon remains the final decision-maker

The final step is not performed by a machine. It is performed by the surgeon. Integration means combining the anatomical information from imaging, the spatial information from navigation, the mechanical assistance of robotics, the visual information from the microscope or exoscope, the cutting characteristics of the ultrasonic bone scalpel, the physiological information from IONM, and the clinical context of the patient.

This leads to the central philosophy of the workflow. One robotic system may help us reach the target. Another may help us see the target. Navigation may show where the working instrument lies. IONM may show how the nervous system is responding. Imaging may verify what has been achieved. Yet none of these systems understands the whole patient. The surgeon must integrate all of them and remain responsible for the final decision.

The future of spine surgery should therefore not be framed as surgeon versus machine. It is better understood as complementary intelligence: technology contributes precision, visualization, localization, reproducibility, and data; the surgeon contributes indication, context, adaptation, tactile judgment, prioritization, and ethical responsibility.

Technology can improve safety only when workflow is disciplined

It is tempting to describe sophisticated technology as making an operation safe. No technology can make complex spine surgery risk-free. Navigation can lose registration. A robotic trajectory can be inappropriate if the plan is inappropriate. A digital image can be misinterpreted. Neuromonitoring can provide misleading information. Equipment can fail. Excellent visualization cannot compensate for poor judgment.

A more defensible statement is that integrated technology can add independent and complementary layers of information that may enhance precision, spatial awareness, reproducibility, and safety. The surgeon and team must remain capable of recognizing when a technology is unreliable and of modifying or continuing the operation safely without it.

This is why workflow discipline is as important as equipment. Operating-table position, robotic access, navigation line-of-sight, screen placement, IONM cables, anaesthesia access, sterile movement, equipment sequence, calibration, troubleshooting, and backup strategies should be planned. A technology-rich operating room without choreography can create congestion, distraction, and new opportunities for error.

Use the right technology for the right pathology

Integration does not mean using every device in every patient. A complex deformity may benefit from three-dimensional imaging, robotic planning, navigation, IONM, and intraoperative verification. A cervical myelopathy may gain more from meticulous visualization, controlled bone removal, navigation of a critical instrument, and neuromonitoring than from robotic instrumentation. An intradural lesion may primarily require advanced optics and physiological monitoring. A minimally invasive lumbar operation may use navigation, robotics, and digital visualization to reduce dependence on repeated fluoroscopy. Revision surgery may particularly benefit from three-dimensional localization when normal landmarks are distorted.

The pathology should dictate the operation, and the operation should dictate the technology. Technology should never dictate the indication.

The educational return may be as important as the technical return

One of the least discussed advantages of the digitally integrated operating room is education. Three-dimensional shared visualization allows trainees to see anatomy that previously only the primary surgeon could appreciate. Navigation and robotics make planning visible: trajectories, landmarks, implant dimensions, and spatial relationships can be discussed in real time rather than remaining only in the mind of the senior surgeon.

For teaching institutions, this has long-term value. The operation becomes a reproducible learning event. Recorded digital visualization can later support case review, morbidity discussion, simulation, and structured teaching. The technology therefore contributes not only to the present patient but also to the training of future surgeons.

Technology must justify itself

Advanced technology carries cost, maintenance requirements, consumables, learning curves, space requirements, and dependence on trained personnel. Newer is not automatically better. Each technology should answer a practical question: Does it improve spatial awareness or precision? Does it improve accuracy or reproducibility? Does it make a difficult operation more achievable? Does it improve workflow, ergonomics, documentation, or education sufficiently to justify its use?

The next stage of technology-enabled spine surgery should therefore be accompanied by measurement. Accuracy, radiation exposure, operative time, blood loss, neurological events, complications, revisions, technology failures, workflow interruptions, costs, ergonomics, and patient-reported outcomes should be studied. Without measurement, technology remains impressive. With measurement, it can become evidence-based.

From navigating screws to navigating the operation

The next transformation may not be another large machine. It may be connectivity. Imaging, navigation, robotics, neuromonitoring, visualization, surgical video, implant information, and postoperative outcomes currently generate large amounts of data that are often interpreted separately. Future operating rooms are likely to connect these streams more directly and provide increasingly context-sensitive support to the surgeon.

The conceptual transition is therefore larger than the move from freehand screws to robotic screws. It is a transition from navigating an implant to navigating progressively more of the operation: the target, the instrument, the physiological response, and the verification of what has been achieved.

While increasing evidence supports the technical accuracy of image-guided, robotic, and augmented-reality-assisted instrumentation, evidence for consistent improvement in patient-level clinical outcomes remains heterogeneous; therefore, these technologies should be viewed as enabling tools rather than independently proven determinants of superior clinical outcomes [7]. The IOTSS concept builds upon the established hybrid operating-room model, extending the integration of intraoperative imaging and navigation to a broader, spine-specific ecosystem of complementary enabling technologies [8]

The destination is not robotics. The destination is better surgery. The most meaningful technology will be technology that helps the surgeon plan more intelligently, see more clearly, know where the instrument is, execute with precision, monitor function, verify the result, and integrate all of that information around the needs of the patient.

Limitations

The data regarding clinical benefits and quantitative institutional data regarding registration accuracy, workflow impact, or complications are currently limited, as the prospective validation studies are in progress. The application of this workflow integration is promising; however, the clinical benefits need to be prospectively studied.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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