



Stereotactic Navigation for Primary Spine and Pelvis Tumour Resection and Reconstruction: A Narrative Review

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Abstract

Spine, sacrum, and pelvic primary tumours are uncommon but are biologically aggressive and for these en bloc resection with clear margins is still the most important factor in achieving local control and long-term survival. Because of the complicated three-dimensional anatomy of these areas — which includes dense neurovascular structures, visceral organs and irregular bony pathways — it has always been difficult to turn the careful preoperative planning into an equally accurate intraoperative cut. Stereotactic (image-guided) navigation, which has long been used in the placement of pedicle screws during degenerative spine surgery, is now being increasingly used as a tool in oncology to assist with osteotomies and to carry out the preoperative resection plans in real time. This review brings together the current body of evidence — based on a 2026 systematic review of 21 studies and 240 patients — regarding the use of navigation in spine and pelvic tumour surgery, the results that have been reported, and the future direction of the technology.

Keywords: Stereotactic navigation; Image-guided surgery; Spine tumor; Pelvic tumor; Sacral chordoma; Chondrosarcoma; En bloc resection; Surgical margins; Tumor reconstruction; Virtual cutting guides

1. Introduction

Spinal and pelvic bone and soft-tissue tumours—these include chordoma, chondrosarcoma, osteosarcoma, Ewing sarcoma, and giant cell tumour—are less common than metastatic spinal disease but cause a much higher level of morbidity due to their position. Different from appendicular sarcomas, in which it is often possible to remove a large amount of normal tissue without any functional effect, spinal and pelvic tumours are situated next to the spinal cord, the cauda equina, the major blood vessels, and the pelvic organs. Consequently, surgeons have to find a resection plane that is sufficient from an oncological point of view and yet one that is anatomically viable.

For a long time the Enneking classification has been the standard in musculoskeletal oncological surgery since wide or marginal ("adequate") resections are linked with a great deal lower rate of local recurrence compared with intralesional ("inadequate") resections, especially in the case of chordoma and spinal sarcomas. It is nevertheless difficult for the surgeon to achieve an Enneking-appropriate margin freehand if he or she is unable to see directly the dorsal or deep extent of the tumour in relation to the bone. This lack of direct visibility is exactly the problem that stereotactic navigation was developed to overcome.

2. The contribution of stereotactic navigation to tumor surgery

Stereotactic navigation systems correlate the patient's anatomy as it happens with a preoperative or intraoperative imaging dataset (such as CT or CT combined with MRI), and then monitor the position of a surgical instrument in space in relation to that registered anatomy—showing the position of the instrument on the images in real time, just like a GPS system. In the case of degenerative and deformity spine surgery this technology is well established for directing the trajectories of pedicle screws. Its use in oncology is based on a different principle: instead of directing an implant into the bone, navigation is used to guide the plane of an osteotomy around the tumour.

Several technical approaches have emerged:

- With the use of computer tomography (CT) during surgery, a preoperative plan is aligned with an intraoperative CT (this is usually acquired using an O-arm or a similar mobile scanner), so that the surgeon can directly trace the planned resection margin on a tracked probe, saw, or drill.
- With the use of MRI-CT fusion navigation, the preoperative MRI—which is better for defining soft tissues and tumor margins—is superimposed onto the intraoperative CT, which is better for displaying bony anatomy, so that the surgeon is given a combined three-dimensional model of the tumour in relation to the bone within the operating room.
- Virtual cutting guides: preoperative computer-aided design (CAD) software is employed, usually with the help of biomedical engineering expertise, to plan the osteotomy lines, after which they are projected onto the intraoperative navigation display as a real-time cutting template – in effect acting as a digital, patient-specific instrument without the need for a physical guide.
- The power instruments were used, including ultrasonic bone scalpels and precision cutting tools which were themselves registered with the tracking system, so that the tip of the cutting instrument—not just a separate pointer—could be tracked during the osteotomy.

3. A summary of the present evidence base

The most thorough synthesis available so far is a systematic review published in 2026 (HSS Journal) which applied the PRISMA methodology in order to find studies that used stereotactic navigation specifically for the resection of primary spine and pelvic tumors, not just for the purpose of instrumentation. This review included 21 studies involving 240 patients, the patients' mean age being 46 years and the mean follow-up period 33.4 months — a suitable duration for evaluating local recurrence in slowly growing tumours such as chordoma.

Key descriptive findings

- The location of the tumour was the sacrum and pelvis in the majority of cases (81.3 per cent), then the thoracic spine (8.3 per cent), after that the cervical spine (5.8 per cent), and finally the lumbar spine (4.6 per cent) — this being due both to the fact that sacral chordomas are disproportionately represented in this body of literature and to the particular anatomical difficulty of carrying out sacral/pelvic osteotomies, which makes navigation especially appealing in those areas.
- Chordoma accounted for 31.7% and chondrosarcoma for 27.1% of the cases, which is in agreement with the general literature regarding primary spinal malignancies.

Pooled outcomes

- The margins were negative in 88.3% of cases (tumor-free surgical margins) and this rate is comparable to that of previous freehand series.
- Local recurrence occurred in 16% of patients as a whole, but there was a great deal of variation

according to histology—chondrosarcoma had the highest rate of recurrence at 32.4%, a result that can be attributed both to its relative resistance to chemotherapy and to radiotherapy and probably also to the technical difficulty of obtaining clear margins in cartilaginous tumours which can have subtle, infiltrative extensions.

- Complications: 30.3% of the patients experienced some kind of complication – a fact that serves as a reminder that these are still major operations no matter whether navigation is used – yet only 1% of the cases (that is, two patients in total) had a complication that can be attributed to the navigation technology itself, indicating that the extra technical component does not significantly increase the risk.
- Regarding comparative data, two studies compared the navigated to non-navigated cohorts. Both suggested improved bony margin accuracy and a lower risk of recurrence linked to the use of navigation, although the authors of the systematic review were rightly cautious about the strength of this comparison due to the small number of studies.

4. Illustrative Applications from the General Literature

Beyond the pooled systematic review, several single- and multi-institution series illustrate how navigation is being deployed in practice:

- A case series involving sacral chordoma employed preoperative MRI combined with intraoperative CT to create three-dimensional tumor reconstructions for the purpose of sacral chordoma resection, and this approach resulted in negative margins in all five of the five planned en bloc operations, with the patients' neurologic function remaining stable or improving after the operation. The MRI-CT fusion method directly tackles the main drawback of using CT alone—namely, that while CT is good at showing bone, it is inadequate in depicting the soft-tissue spread of a tumour, whereas MRI does this much better.
- For sacropelvic resections, a group from a major cancer centre employed CAD-based virtual cutting guides in combination with an ultrasound-powered cutting instrument to carry out navigated osteotomies in six patients having an en bloc sacral/pelvic tumor resection, and obtained negative margins in all patients at short-term follow-up. This method is in effect a digital version of the 'cutting guide' idea already known from patient-specific instrumentation made using 3D printing, since it does not require a physical device to be manufactured and sterilised in advance.
- The ultrasonic bone scalpel was guided by a navigation system; technical reports state that the ultrasonic bone scalpel is registered directly to the navigation platform so that the cutting instrument itself—not a separate tracked pointer—is shown in real time in relation to the tumour margin, enabling the surgeon to keep a defined safety margin (for example, ≥ 5 mm) during the osteotomy.
- The use of CT-based navigation for both the reconstruction and the resection. A case-series study from Korea which employed CT-based navigation for both spinal tumour resection and the subsequent reconstruction found negative margins in six out of seven patients (85.7 per cent), with no intraoperative complications related to the navigation, thus demonstrating that the value of navigation goes beyond the resection phase to include accurate placement of hardware during reconstruction of the resulting bony defect.
- When it comes to malignancies of the pelvic bone. A review that concentrated on the use of computer-assisted navigation and robotics in both primary and metastatic pelvic bone cancers also arrived at a similar conclusion: navigation has been linked to a higher rate of negative-margin resection, though long-term oncological outcomes in relation to navigation have not yet been firmly established, and its application in percutaneous stabilization of pelvic metastases is still in its early stages.

5. Interpreting the Evidence: Its Advantages and Disadvantages

When the literature is considered as a whole, several themes appear.

- The reason is anatomically sound since the sacrum and pelvis—because it is in these areas that the majority of navigated tumour cases begin—is where freehand orientation is most difficult and where the consequences of a misjudged margin (such as a violation of the tumour capsule or the unnecessary sacrifice of nerve roots) are most severe. It therefore makes sense that navigation clusters in these areas.
- Although the margin and recurrence data are promising they are not yet conclusive. The figure of 88.3% for a negative margin and an overall recurrence rate of 16% are acceptable, but the authors of the systematic review have rated the evidence as Level IV—that is, a systematic review consisting mainly of Level III and IV studies. Nearly all of the studies included in the

review were retrospective case series and did not have contemporaneous non-navigated controls, and although the two comparative studies that were available were in favour of navigation, they are too few to allow for a strong causal conclusion.

- More importance is attached to histology than many people realise. The sharp contrast in the rate of recurrence between chordoma-type and chondrosarcoma-type tumours (32.4% for chondrosarcoma as compared with the overall pooled figure of 16%) serves as a reminder that navigation is a tool which enhances the accuracy of a treatment plan— it cannot entirely make up for the inherently invasive or satellite-lesion behaviour that chondrosarcoma is known to show.
- Safety seems promising. The fact that the rate of complications attributable to navigation is very low (1%) in contrast to the high overall complication rate (30.3%) indicates that the majority of morbidity in these operations is due to the extent and site of the surgery itself — for example, substantial blood loss, a long operative time, and the proximity to neurovascular structures — rather than to the navigation technology. Other series which have reported complex en bloc resections in the mobile spine also show similarly high complication rates (in some small groups as high as 90%) and very long operative times, which shows that these procedures still remain among the most demanding in musculoskeletal surgery no matter whether navigation is used.
- Registration accuracy represents a practical bottleneck. In the wider field of navigation, fiducial registration error is generally in the order of a few millimetres. In the case of tumours where the intended margin is only a few millimetres beyond grossly normal tissue, registration accuracy is by no means a mere technicality—it directly affects whether the 'navigated' margin corresponds to the 'achieved' margin.

6. Future Directions

Several trends are likely to shape the next generation of evidence in this space:

- It is necessary to carry out larger, prospective, and multi-institutional comparative studies if we are to go beyond the retrospective single-arm series and to better determine the independent contribution of navigation to margin status and recurrence while taking into account surgeon experience and tumor histology.
- The combination of navigation with robotics and with navigated power instruments (since this has already been done using ultrasonic bone scalpels and CAD-based virtual cutting guides) could further decrease the gap between the planned and the carried out osteotomy, especially in anatomically restricted areas such as the high sacrum or the pelvic ring.
- Standardized outcome reporting — consistent definitions of margin status, recurrence, and navigation-specific complications — would materially improve the ability to pool future data, an explicit limitation noted by the 2026 systematic review given the heterogeneity in methodology, tumor type, and follow-up across the included studies.
- Cost-effectiveness and learning-curve data remain sparse; as with any capital-intensive technology, adoption outside high-volume tertiary sarcoma centers will likely depend on evidence that outcomes benefits persist even as the technology is used by a broader range of surgical teams.

7. Conclusion

Stereotactic navigation has moved from a tool for spinal instrumentation into a genuine oncologic adjunct for the resection and reconstruction of primary spine and pelvic tumors. The best current evidence — pooled from 21 studies and 240 patients — shows negative margins achieved in nearly 9 of 10 navigated cases, an overall local recurrence rate of 16% (concentrated in chondrosarcoma), and a navigation-attributable complication rate of only about 1%, against a substantial background complication rate inherent to these operations. Comparative data, while still limited to two studies, favor navigation over freehand technique for bony margin accuracy and recurrence risk. The evidence is not yet Level I, and the field would benefit from larger prospective comparative trials, standardized outcome definitions, and continued integration with complementary technologies such as virtual cutting guides and navigated power instruments. For now, stereotactic navigation should be regarded as a promising, safe, and increasingly well-supported adjunct — not yet a proven standard of care, but a technology with a clear anatomic rationale and a growing evidence base in favor of its adoption at experienced sarcoma centers.

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