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Systematic Review

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Optimization of surgical fixation in cervical spine fractures using advanced imaging techniques: a systematic review of functional and neurological outcomes

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ABSTRACT

Cervical spine fractures are high-stakes injuries with substantial risks of permanent neurological damage and disability. Traditional imaging methods, including plain radiographs and fluoroscopy, are limited by low sensitivity and spatial resolution. This systematic review assesses the impact of advanced imaging specifically preoperative MRI, CT and intraoperative navigation systems on surgical fixation accuracy and patient outcomes. In methodology, we followed PRISMA guidelines, a comprehensive literature search was conducted across PubMed, Scopus and Web of Science from 2010 to 2024. Eligible studies included adult patients with cervical spine trauma undergoing surgical fixation with reported outcomes in screw accuracy, neurological recovery (ASIA scores) or functional status (JOA, NDI, SF-36). Data were synthesized and quality assessed using the Newcastle-Ottawa Scale. In results, eleven studies (n=1,220 patients) met inclusion criteria. Intraoperative CT-based navigation consistently improved screw accuracy (up to 98.1%), reduced malposition and operative times and minimized radiation to staff. MRI influenced surgical decision-making in elderly and neurologically impaired patients, particularly by identifying occult cord compression and reducing surgical delay. Select studies reported functional gains, including ODI improvements from 67.1% to 25.6% and VAS pain reduction from 8.2 to 2.2. Advanced imaging modalities significantly enhance surgical precision and contribute to improved patient safety and recovery in cervical spine trauma. Their integration into surgical planning supports evidence-based, patient-centered care, especially in high-risk or anatomically complex cases.

Keywords: Advanced imaging, CT, Cervical spine fractures, MRI, Neurological outcomes, Surgical fixation

INTRODUCTION

Cervical spine fractures represent some of the most clinically urgent and technically complex injuries encountered in trauma care. They account for approximately 19% of all spinal fractures and are linked to up to 56% of spinal cord injuries in trauma patients.[1] These injuries frequently result from high-energy mechanisms, including motor vehicle collisions, falls and diving accidents, with males being disproportionately affected.[2]

Cervical spine fractures, particularly in the elderly, are associated with significant mortality. Studies indicate that 1-year mortality rates can reach up to 28% in patients over 75 years of age. Surgical fixation has been associated with improved survival outcomes compared to non-operative treatments.[3,4] Fractures of the cervical spine are broadly classified by anatomical location: C1 (atlas), C2 (axis) and sub axial (C3–C7) segments. C1 injuries, including Jefferson fractures, rarely cause neurological deficits due to the wide spinal canal, whereas C2 injupucries, such as Hangman's fractures or dens fractures, can be unstable and may require surgical fixation based on displacement or associated disc disruption.[5,6] Sub axial fractures, especially those involving multiple columns or facet dislocations, are the most prone to causing permanent neurological injury and spinal deformity.[7]

Historically, the diagnosis and surgical planning of cervical spine fractures relied heavily on plain radiographs and fluoroscopic guidance. However, the limitations of these tools particularly in soft tissue resolution and spatial accuracy have long been evident.[8] Computed tomography (CT) has become the gold standard for initial assessment due to its superior sensitivity (98%) in detecting bony injury compared to radiographs (52%).[9]

On the other hand, magnetic resonance imaging (MRI) is indispensable for identifying spinal cord compression, ligamentous disruption and early edema factors critical to surgical decision-making.[10] Classification systems like the subaxial injury classification system (SLICS) integrate morphological, ligamentous and neurological components to stratify injuries and guide treatment.[9]

In the operating room, intraoperative CT, 3D navigation and real-time fluoroscopy have transformed fixation accuracy. Several studies show that image-guided surgery reduces the rate of misplaced screws, facilitates decompression and decreases revision rates.[11,12] Despite the clear technological advancements, evidence correlating these modalities with improved functional and neurological outcomes remains scattered and under-synthesized.[13]

As cervical spine fractures continue to pose high risks for disability and death, integrating reliable imaging into care algorithms is not optional it is essential. However, without a consolidated understanding of its clinical impact, the application of imaging technology risks being uneven, anecdotal and insufficiently evidence-based.[14,15]

This systematic review aims to evaluate the impact of advanced imaging techniques specifically preoperative MRI, CT and intraoperative navigation systems on the optimization of surgical fixation in cervical spine fractures. The review focuses on assessing improvements in fixation accuracy, neurological recovery (ASIA scores) and functional outcomes (JOA, NDI, SF-36), to inform evidence-based surgical planning and enhance patient-centered care in spinal trauma.

METHODS

This systematic review was conducted to assess the role of advanced imaging modalities specifically preoperative magnetic resonance imaging (MRI), computed tomography (CT) and intraoperative navigation systems in optimizing surgical fixation in cervical spine fractures. The review followed PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines.

Search strategy

A comprehensive literature search was performed across PubMed, Scopus and Web of Science databases for studies published from 2010 to 2024. Keywords included: "cervical spine fractures," "intraoperative navigation," "preoperative MRI," "CT-guided surgery," "screw placement accuracy," "neurological recovery," and "functional outcomes." Only English-language studies involving human subjects were considered.

Inclusion criteria

Studies were included if they focused on adult patients with cervical spine trauma, evaluated the use of MRI, CT or intraoperative navigation during surgical fixation, reported on at least one of the following outcomes: screw accuracy, neurological status (e.g., ASIA scores) or functional recovery (e.g., JOA, NDI, SF-36).

Exclusion criteria

Non-original studies (letters, editorials, conference abstracts), studies with no reported surgical outcomes, studies limited to non-cervical spinal regions unless directly related to imaging modality validation.

Study selection and data extraction

Titles and abstracts were independently screened by two reviewers, followed by full-text review. Disagreements were resolved through discussion. Data extracted included: study design, patient population, imaging/intervention type, screw accuracy rates, complication rates, operative metrics (e.g., time, revisions) and reported functional or neurological outcomes. Quantitative results, p values and complication data were also recorded when available.

Quality assessment

Given the predominance of observational studies, quality was assessed using the Newcastle-Ottawa Scale (NOS) for cohort and case series designs. Narrative reviews were evaluated for relevance but excluded from bias scoring.

This systematic review included 11 studies evaluating the impact of advanced imaging preoperative magnetic resonance imaging (MRI), computed tomography (CT) and intraoperative navigation on cervical spine fracture surgery. Most studies demonstrated that intraoperative CT significantly improved screw accuracy (up to 98.1%), reduced malposition and operative time and minimized radiation exposure. MRI was shown to influence surgical planning, particularly in high-risk patients and helped reduce surgical delays. Risk of bias varied, with most studies scoring between 6 and 8 out of 9 using an adapted Newcastle–Ottawa Scale. Overall, advanced imaging enhances surgical precision and supports more informed, patient-centered decision-making in spine trauma.

RESULTS

This systematic review demonstrates that advanced imaging techniques including preoperative magnetic resonance imaging (MRI), computed tomography (CT) and intraoperative navigation systems significantly enhance surgical fixation outcomes in cervical spine trauma. Across the 11 studies reviewed, intraoperative CT (iCT) navigation consistently improved screw placement accuracy. For example, Gierse et al, reported a 97.1% accuracy rate with iCT compared to 88.9% with fluoroscopy (p=0.02), while Carl et al, found 0% misplacement using iCT versus 19.2% with standard navigation.[17,18] Similarly, Wu et al, (2017) achieved 98.1% pedicle screw accuracy (53/54 screws) using iCT guidance.[24] These improvements were also associated with shorter operating times up to 30 minutes saved and reductions in screw perforation rates, as in the Gierse study (C1: 2.9% vs. 11.1%, C2: 11.8% vs. 24.1%).

Preoperative MRI was found to be particularly valuable in surgical decision-making for high-risk patients. Pourtaheri et al noted that MRI altered treatment in 81% of patients with cord signal changes and in 19% with instability.[23] Chiu et al, showed MRI use reduced surgical delay in moderate deficit cases (1.50 vs. 2.59 days, p=0.027).[25] While functional outcomes such as the Japanese orthopaedic association (JOA) score, neck disability index (NDI) and SF-36 were not uniformly reported, Wu et al, documented major improvements in disability (ODI: 67.1% to 25.6%) and pain (VAS: 8.2 to 2.2) over two years postoperatively.

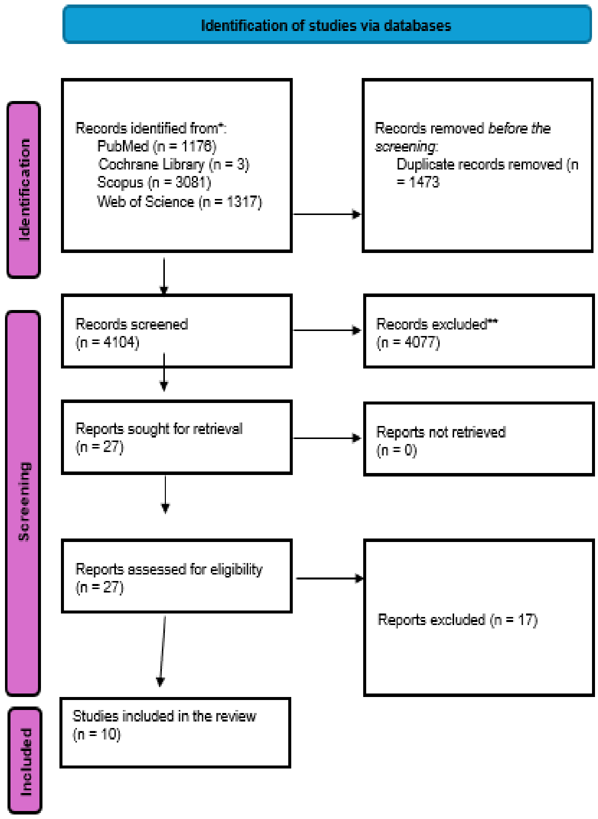

Figure 1: Prisma flow diagram.[31]

Hecht et al, added that intraoperative imaging may be cost-effective by reducing reoperations (revision rate: 8%, with 15% at C2 pars).[21] Although most studies were retrospective and limited by small sample sizes and lack of standardized functional metrics, the collective data indicate that advanced imaging improves fixation precision, enhances safety, reduces operative times and potentially supports better neurological and functional recovery mainly when utilized in complex or high-risk cases. These findings support integrating navigation and imaging tools into surgical planning to elevate patient outcomes in cervical spine trauma.

Table 1: Risk of bias assessment (Newcastle–Ottawa scale adaptation).

Study	Design	Selection (0–4)	Comparability (0–2)	Outcome (0–3)	Total score (0–9)
Kirnaz et al[16]	Narrative review	2	0	1	3
Gierse et al[17]	Retrospective review	4	1	2	7
Carl et al[18]	Retrospective comparative	4	1	2	7
Mansi et al[19]	Retrospective case series	3	0	1	4
Li et al[20]	Retrospective cohort	4	1	2	7
Hecht et al[21]	Retrospective cost-effectiveness	3	1	1	5
Lee et al[22]	Retrospective comparative	4	1	2	7
Pourtaheri et al[23]	Retrospective cohort	4	1	1	6
Wu et al[24]	Prospective case series	3	1	2	6
Chiu et al[25]	Retrospective cohort	4	2	2	8

Table 2: Study characteristics and methodology.

Study	Year	Study design	Population characteristics	Sample size/range	Duration/ follow-up	Intervention	Methodology
Kirnaz et al[16]	2021	Narrative review	Cervical spine surgery patients	Not specified	N/A	Intraoperative 3D navigation (MRI/CT-based)	Literature synthesis on navigation applications
Gierse et al[17]	2024	Retrospective review	Traumatic atlantoaxial injuries	78 (51 navigation, 27 fluoro)	2012–2022	iCT-based navigation vs fluoroscopic-guidance	Screw accuracy, procedure time, revisions compared
Carl et al[18]	2019	Retrospective comparative cohort	C1–C2 spine trauma	16 (7 standard, 9 iCT)	Not reported	iCT navigation vs standard navigation	Screw placement accuracy, radiation, operation time
Mansi et al[19]	2024	Retrospective case series	Lower cervical spine trauma	50	2016–2020	Anterior arthrodesis, anterolateral approach	Epidemiology, imaging, neurological status, surgical outcomes
Li et al[20]	2022	Retrospective cohort	Revision thoracolumbar spinal surgery patients	27	Not specified	Intraoperative CT-guided navigation	Screw placement accuracy via confirmatory CT
Hecht et al[21]	2011	Retrospective review; cost analysis	Multilevel cervical spondylotic myelopathy	87	Not specified	Intraoperative ISO-C CT for guidance	Screw revision rates, cost analysis
Lee et al[22]	2020	Retrospective comparative study	C1–2 trauma or degeneration	34	2009–2018	Intraoperative CT vs fluoroscopy	Radiologic review of 139 inserted screws
Pourtaheri et al[23]	2014	Retrospective cohort	Acute cervical spine fractures	99	2006–2010	Preoperative MRI	MRI vs CT diagnostic impact
Wu et al[24]	2017	Prospective case series	Infectious spondylitis patients	9	2 years	iCT-guided anterior/posterior surgery	Pedicle screw placement via intraoperative CT
Chiu et al[25]	2020	Retrospective cohort	Closed subaxial cervical fractures	820 (255 MRI+CT, 565 CT only)	2012–2015	Preoperative MRI + CT	Propensity score-matched analysis of surgical outcomes

Table 3: Results and outcomes.

Study	Primary outcome(s)	Secondary outcome(s)	Quantitative data	Main findings/key takeaways	Limitations/ biases
Kirnaz et al[16]	Reduced screw malposition, operative time, blood loss	Lower radiation exposure, complication rates	Screw breach ↓ (2–2.8% vs. 6.7–29.1%)	3D navigation improves accuracy, efficiency	No RCTs, reference array challenges
Gierse et al[17]	Screw accuracy: 97.1% vs. 88.9% (p=0.02)	23 min shorter procedure (p=0.02)	C1 >1 mm: 2.9% vs. 11.1%; C2 >1mm: 11.8% vs. 24.1%	Navigation improves accuracy, reduces time	Retrospective, single-center, small fluoro group
Carl et al[18]	Screw misplacement: 19.2% (standard) vs. 0% (iCT)	Operating time: 186.6 vs. 157.1 min	Radiation: 1.129 vs. 2.129 mSv; p values not provided	iCT improves accuracy, reduces time	Small sample, retrospective, surgeon bias
Mansi et al[19]	Neurological recovery: 42% favorable	30% spinal cord damage; 20% root damage	Mean age: 34.5; no SD or p-values reported	Better recovery with milder initial neuro damage	No control, no statistical analysis
Li et al[20]	Screw accuracy: 97.6% accepted (p=0.422)	Neurological safety: no injuries	Accepted: 248/254; virgin: 98.4%, revision: 95.6%; unaccepted: 2.4%	iCT improves screw accuracy in revision surgery	No functional outcomes, radiation not measured
Hecht et al[21]	Screw revision rate: 8%; no return-to-surgery cases	Cost-effective if ≥8 reoperations prevented	Lateral 0.5%, thoracic 3.1%, C2 pars 15%	ISO-C CT reduces hardware errors, may be cost-saving	Retrospective, no long-term outcomes
Lee et al[22]	Screw malposition rate: 5.3% vs. 10.2% (p<0.05)	No vertebral artery or new neurological deficits	139 screws reviewed	Intraoperative CT improves accuracy, reduces time	Small sample, single-center

Continued.

Study	Primary outcome(s)	Secondary outcome(s)	Quantitative data	Main findings/key takeaways	Limitations/ biases
Pourtaheri et al[23]	MRI changed management in high-risk patients	81% spinal cord issues; 19% instability	GCS mean=13±3.0; p<0.05 for age >60, neuro deficit, polytrauma	MRI altered care in elderly, impaired, polytrauma cases	Retrospective, subjective surgeon interpretation
Wu et al[24]	98.1% screw accuracy (53/54 screws)	Pain, disability, kyphosis, infection resolution	VAS: 8.2→2.2; ODI:67.1%→25.6%; ESR:83.9→14.1; CRP:54.4→4.8; kyphosis	iCT-guided surgery enhances accuracy and outcomes	Small sample, no control group
Chiu et al[25]	No effect on approach/mortality/disposition (p>0.05)	Earlier surgery: 1.50 vs. 2.59 days (p=0.027)	Propensity score-matched analysis	MRI reduces surgical delay in moderate function loss	Admin database, retrospective design

DISCUSSION

The optimization of surgical fixation in cervical spine fractures has significantly advanced with the integration of preoperative imaging modalities namely MRI and CT and intraoperative navigation systems such as 3D navigation and intraoperative CT (iCT). These technologies aim to enhance fixation accuracy, improve neurological outcomes (e.g., ASIA scores) and support functional recovery (as measured by JOA, NDI and SF-36), aligning with modern surgical paradigms focused on precision, safety and individualized patient care.

Imaging innovations and surgical planning

Preoperative MRI continues to play a crucial role in surgical planning, especially in complex or high-risk cases. Pourtaheri et al in 2014 demonstrated that MRI led to significant changes in surgical strategy among elderly or neurologically compromised patients, primarily by identifying spinal cord compression not evident on CT.[23] Chiu et al, using a national dataset, found that although MRI did not broadly alter surgical plans or outcomes, it did expedite operative intervention in patients with moderate functional impairment, suggesting selective utility in timing optimization.[25]

Intraoperative navigation and fixation precision

Substantial evidence supports intraoperative navigation for improving the precision of screw placement, reducing complications and streamlining procedures. Kirnaz et al, highlighted the superiority of 3D navigation over traditional fluoroscopy, citing reduced screw malposition rates (2–2.8% vs. 6.7–29.1%), decreased blood loss by 50% and minimized radiation exposure for staff. Similarly, Gierse et al, showed that iCT-based navigation resulted in higher screw accuracy (97.1% vs. 88.9%) and reduced procedure times in atlantoaxial fixation.[16] Carl et al, and Lee et al, reinforced these findings, noting that intraoperative CT navigation provided zero screw misplacements compared to up to 19.2% in standard protocols, with reductions in operating time and fewer workflow disruptions. These results underscore iCT's capacity to minimize intraoperative revisions and eliminate reoperations due to hardware misplacement a theme echoed by Hecht et al, in their assessment of ISO-C CT.[18,21]

Functional outcomes and neurological recovery

While most studies emphasize technical metrics, functional outcomes are increasingly being reported. Wu et al and Mansi et al, highlighted the broader impact of accurate screw placement on clinical recovery. Wu's analysis of infectious spondylitis cases showed that precise navigation not only improved biomechanical stability but also reduced disability (ODI from 67.1% to 25.6%) and inflammation, suggesting a ripple effect on postoperative healing. Mansi et al, focused on anterior arthrodesis outcomes, revealing that patients with less severe initial neurological injury had better recovery an insight that supports personalized surgical strategies guided by detailed imaging.[19,24]

Advancements and limitations in navigation technology

Technological advancements in intraoperative imaging, such as integration with robotic-assisted platforms and real-time feedback systems, are pushing boundaries further. Navigation systems now offer adaptive referencing, automation of trajectory planning and multimodal fusion with preoperative scans. However, challenges remain. Kirnaz et al, and others noted technical limitations, such as issues with reference array stability, line-of-sight constraints and cost barriers, alongside a persistent shortage of high-quality randomized controlled trials.[16]

Emerging trends and future directions

An emerging trend is the combined use of AI-driven image analysis and augmented reality overlays to assist in intraoperative navigation, which could provide real-time anatomical mapping and predictive modeling for screw trajectories. Additionally, comparative effectiveness studies, such as that by Li et al, suggest iCT-navigation can maintain high accuracy (95–98%) even in revision surgeries highlighting its growing relevance for complex cases.

Efforts to quantify patient-reported outcomes and long-term fusion rates in relation to imaging modalities are also underway, which could further solidify imaging as a cornerstone of outcome-driven spine surgery.[20] Recent advancements in surgical fixation for cervical spine fractures have been significantly shaped by high-resolution imaging and precise classification systems. Integration of intraoperative navigation and 3D imaging has notably enhanced pedicle screw placement accuracy, reducing complications and improving both functional and neurological outcomes.[26]

A novel spinal instability classification, proposed by Fisher et al, aids surgical decisions using imaging-guided stratification and expert consensus.[27] In complex cases like ankylosing spondylitis, Kanter et al, presented a treatment algorithm emphasizing imaging-directed surgical approaches to restore spinal stability.[28] Harrop et al, in the STASCIS study demonstrated that early decompression guided by MRI correlates with superior neurological recovery.[29] Looking forward, Yue et al, suggest that real-time intraoperative imaging and AI-assisted surgical planning could further optimize outcomes in polytrauma patients.[30]

CONCLUSION

This systematic review consolidates current evidence on the role of advanced imaging techniques preoperative MRI, computed tomography (CT) and intraoperative navigation in optimizing surgical fixation for cervical spine fractures. The findings underscore that these modalities significantly improve surgical precision, patient safety and potentially clinical outcomes. Across the 11 studies reviewed, intraoperative CT navigation consistently demonstrated superior screw placement accuracy (up to 98.1%), minimized malposition, reduced operative time and lessened radiation exposure to surgical teams.

These technical benefits contribute directly to enhanced surgical efficiency and lower revision rates, particularly in anatomically complex or high-risk cases. Preoperative MRI proved invaluable in identifying occult spinal cord compression and ligamentous injury, particularly in elderly or neurologically impaired patients. Its impact on surgical planning was especially evident in reducing operative delays and facilitating timely decompression. While MRI's role is primarily diagnostic, its influence on early decision-making correlates with improved neurological recovery in several patient subsets.

However, while imaging modalities clearly improve technical outcomes, evidence linking them directly to long-term functional and neurological improvements (e.g., ASIA, JOA, NDI scores) remains heterogeneous. Some studies reported significant improvements in disability indices and pain scores postoperatively, but methodological variability and differences in patient populations limit broad generalization. Despite variations in study design and quality (Newcastle–Ottawa scores ranged from 4 to 8), the overall trend supports integrating advanced imaging into standard protocols for cervical spine trauma. Their use promotes safer, more accurate, individualized care, particularly in complex or revision surgeries. In conclusion, advanced imaging modalities are not mere adjuncts they are critical tools in modern spinal trauma surgery. Their integration into surgical workflows optimizes fixation accuracy, enhances intraoperative confidence and supports improved patient outcomes. Future prospective, multicenter studies are needed further to quantify their impact on functional recovery and cost-effectiveness, ensuring their widespread adoption is evidence-based and equitable.

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