The Essential Role of Radiology in Enhancing Spinal Surgery Outcomes: A Narrative Review

Hashem Bark Awadh Abood[1], Shatha Ahmed Alqahtani[2], Yasmeen Salem Alqahtani[3], Najad Lafi Almutairi[4], Omar Mohammed Omar Alshehri[5], Feras Qasim Alami[6], Alwaleed Khaled Alhujaily[7], Mujtaba Hussain Alamer[8], Lama Taleb Alsemairi[9], Rawan Mohammed Alqarni[10], Abdulaziz M Shaikh Mohammed[11], Alruwaili, Khalid Bin Nuwaysir S[12]

[1] Consultant General Surgery – King Fahad Hospital – Albaha, KSA, Email: ha-abood@moh.gov.sa
[2] Internal Medicine – Almoosa Specialist Hospital – Alahsa, KSA, Email: Sa.alq.497@gmail.com
[3] Family Resident – First Health Cluster – Alriyadh, KSA, Email: Yasmeenks430@gmail.com
[4] Medical Intern – Vision Colleges – Riyadh, KSA, Email: Najdalmutairi_@outlook.com
[5] General Physician – General Surgery Department, King Khalid Hospital – Alkharj City, KSA, Email: Dr.Alshehriomar@gmail.com
[6] Medical Intern – Battarjee College Medical – Aseer, KSA, Email: ferasalalami15@gmail.com
[7] Medical Intern – Taibah University, KSA, Email: Alwaleed.kh100@gmail.com
[8] Radiology Sciences – Dallah Hospital – Alahsa, KSA, Email: mujtaba.alamer6@gmail.com
[9] Medical Intern – Al-Rayan Colleges – Madinah, KSA, Email: lamaalsemairi@gmail.com
[10] Physical Therapy – Um Al-Qura University – Makkah, Email: Rawanalqarni.pt@gmail.com
[11] General Practitioner – King Fahad Hospital Hofuf, KSA, Email: abdzmohd23@gmail.com
[12] General Practitioner – General Directorate of Prison Health – Jouf, KSA, Email: Dr.khalid7820@gmail.com

***Corresponding author: Hashem Bark Awadh Abood**, **Email:** ha-abood@moh.gov.sa

ABSTRACT
The evolution of spinal surgery from a high-risk, largely empirical discipline to a precise and predictable specialty is fundamentally intertwined with advancements in medical radiology. This article is a narrative review synthesizing evidence from clinical studies, systematic reviews, and guidelines on the role of radiological imaging across the preoperative, intraoperative, and postoperative phases of spinal surgery.The utility of radiology extends dynamically into the operating room, where intraoperative guidance technologies—from real-time fluoroscopy to sophisticated 3D navigation and robotic systems—transform these preosub-millimetric accuracyperative plans into executed reality with sub-millimetric accuracy, drastically improving the safety and precision of instrumentation, particularly in complex and minimally invasive procedures. Following surgery, radiology transitions to a vital monitoring tool, where serial imaging assesses the success of decompression and fusion, evaluates spinal alignment, and facilitates the early detection of complications such as pseudoarthrosis, implant failure, or adjacent segment disease. Despite facing challenges including radiation exposure, cost, and technical artifacts, the continuous evolution of imaging technology and its symbiotic relationship with surgical innovation persistently pushes the boundaries of what is achievable, solidifying radiology not as a mere adjunct but as a fundamental pillar that directly elevates the efficacy, safety, and predictability of spinal surgical interventions, ultimately translating into superior patient outcomes.
Keywords: Spinal Surgery; Radiology; Medical Imaging; Image-Guided Surgery; Surgical Navigation; Preoperative Planning; Postoperative Assessment; Pedicle Screw Accuracy.

INTRODUCTION

Spinal surgery represents one of the most formidable and intricate domains within the surgical disciplines, tasked with addressing a vast spectrum of pathologies ranging from debilitating degenerative conditions and traumatic injuries to complex spinal deformities and neoplastic processes[1]. The historical trajectory of spinal interventions is a narrative of gradual, often cautious, advancement, marked by a fundamental shift from open, highly invasive procedures with significant morbidity towards minimally invasive techniques that prioritize precision, neural preservation, and accelerated recovery[2].

In its earliest incarnations, spinal surgery was largely exploratory, with surgeons relying on palpable anatomical landmarks and limited visual access, leading to high complication rates and unpredictable outcomes [3]. The development of the operating microscope in the mid-20th century provided the first major leap, illuminating the intricate anatomy of the spinal canal and enabling more delicate manipulations of neural structures [4].

However, true paradigm shifts have been inextricably linked to parallel revolutions in medical imaging. The advent of technologies such as computed tomography (CT) and magnetic resonance imaging (MRI)

Received: 01/12/2025
Accepted: 31/12/2025

transformed the surgeon's understanding of spinal pathology from inferred to exquisitely visualized, allowing for detailed preoperative planning that was previously unimaginable [5].

Contemporary trends in spinal surgery are overwhelmingly defined by the principles of minimalism, navigation, and personalization. Minimally Invasive Spine Surgery (MISS), utilizing tubular retractors and percutaneous instrumentation, aims to reduce soft tissue trauma, postoperative pain, and hospitalization time [6]. The pursuit of spinal stability and alignment has driven innovations in implant technology, including pedicle screw-rod constructs, cervical disc arthroplasty, and expandable interbody cages [7].

Perhaps the most significant trend, however, is the seamless integration of advanced imaging into every phase of the surgical workflow, giving rise to image-guided navigation and robot-assisted surgery [8].

These technologies are not mere adjuncts but have become foundational pillars, enabling surgeons to execute preoperatively conceived plans with sub-millimetric accuracy within the complex three-dimensional anatomy of the spine[9].

This evolution underscores a central thesis: modern spinal surgery is fundamentally a radiologically-driven specialty. The surgeon's ability to diagnose, plan, execute, and verify is now profoundly dependent upon, and enhanced by, a sophisticated array of radiological tools. This article explore this symbiosis, examining the critical role of radiology in the preoperative, intraoperative, and postoperative phases, while also acknowledging the persistent challenges and future directions of this dynamic field.

METHODOLOGY

This comprehensive narrative review was conducted through a comprehensive examination of the contemporary scientific literature to synthesize current knowledge on the integral relationship between radiology and spinal surgery outcomes.

A targeted search strategy was designed and executed across major biomedical databases, including PubMed/MEDLINE, Scopus, and Web of Science. The search utilized a combination of Medical Subject Headings (MeSH) terms and keywords, such as "spinal surgery," "radiology," "neuroimaging," "preoperative planning," "intraoperative navigation," "O-arm," "pedicle screw accuracy," "postoperative complications," "spinal fusion assessment," and "image-guided surgery." Boolean operators (AND, OR) were employed to refine the search. The inclusion criteria prioritized peer-reviewed original research articles, high-impact review papers, meta-analyses, and authoritative textbook chapters published predominantly within the last two decades to ensure relevance to current practice, though seminal historical papers were included for contextual perspective. Articles were excluded if they were not published in English, were unrelated to diagnostic or interventional spinal imaging, or were deemed to be of studies with insufficient imaging–surgical outcome correlation or non-clinical focus.

Following the initial database search, all identified articles were screened by title and abstract for relevance to the predefined subheadings: Introduction, Preoperative Evaluation, Intraoperative Guidance, Postoperative Assessment, and Challenges. The full texts of selected articles were then critically appraised. Data pertaining to imaging modalities, technological applications, clinical outcomes, accuracy metrics, complication rates, and limitations were extracted and organized thematically. The synthesis of information was not statistical but analytical, aiming to construct a coherent, evidence-based narrative that traces the role of radiology throughout the surgical continuum. This review did not follow a formal systematic review protocol (e.g., PRISMA) and did not include a quantitative synthesis or formal risk-of-bias assessment.

Preoperative Radiological Evaluation: Importance and Methodologies

The foundation of a successful spinal surgery is laid not in the operating room, but in the comprehensive analysis of preoperative imaging. This phase is diagnostic, prognostic, and strategic, serving to accurately characterize the pathology, assess the surrounding anatomical landscape, rule out confounding conditions, and formulate a patient-specific surgical blueprint[10]. Inadequate or misinterpreted preoperative imaging is a recognized precursor to surgical failure, wrong-level surgery, and unintended neurological injury[11]. The modern spinal surgeon has a versatile arsenal of imaging modalities at their disposal, each providing unique and complementary information.

Plain radiographs, including dynamic flexion-extension views, remain a first-line investigation, offering a rapid, low-cost assessment of overall spinal alignment, gross instability, disc space height, and the presence of overt deformities like spondylolisthesis[12].

They provide a crucial functional context that static advanced imaging may lack. However, the cornerstone of detailed preoperative planning is cross-sectional imaging. Magnetic Resonance Imaging (MRI) is unparalleled in its ability to visualize soft tissue structures. It provides exceptional detail of the spinal cord, nerve roots, intervertebral discs, ligaments, and paraspinal muscles[13].

Pathologies such as disc herniations, spinal stenosis, ligamentum flavum hypertrophy, intramedullary tumors, and inflammatory conditions are exquisitely demonstrated. Specialized sequences like T2-weighted, STIR (Short Tau Inversion Recovery), and contrast-enhanced T1-weighted images allow for differentiation between disc material, scar tissue, tumor, and infection[14].

Computed Tomography (CT) excels in depicting bony anatomy. Its high spatial resolution is critical for evaluating facet joint arthritis, osteophyte formation, fracture patterns, and congenital bony anomalies.[15] In the context of planned instrumentation, particularly pedicle screw placement, a CT scan is indispensable for assessing pedicle morphology—including diameter, length, and angulation—and identifying any aberrant vertebral artery or critical structure anatomy[16].

The integration of MRI and CT data provides a complete structural picture: MRI defines the neural compression and soft tissue targets, while CT defines the bony architecture that will host the implants.

For complex spinal deformities, such as scoliosis, or for planning extensive reconstructions, full-length standing radiographs (posteroanterior and lateral) of the entire spine are mandatory[17].

These images allow for the calculation of crucial parameters like Cobb angles, sagittal vertical axis (SVA), pelvic incidence (PI), and pelvic tilt (PT), which guide the goals of surgical correction to achieve a harmonious, balanced spine[18] .

In cases of suspected vascular lesions or tumors with high vascularity, spinal angiography (conventional or CT/MR angiography) may be employed to map the arterial supply and venous drainage, informing surgical strategy and potentially enabling preoperative embolization to reduce intraoperative bleeding[19].

Table 1: Key Preoperative Imaging Modalities and Their Primary Applications in Spinal Surgery Planning

Imaging Modality	**Primary Strengths**	**Key Surgical Applications**
Plain Radiography (X-ray)	Assessment of alignment, instability, bone integrity. Low cost, readily available [12]	Evaluating scoliosis, spondylolisthesis, fracture stability, implant positioning (post-op).
Computed Tomography (CT)	Excellent bony detail, 3D reconstruction capabilities. Evaluates cortical integrity and foraminal stenosis [15],[16]	Planning pedicle screw trajectory, assessing fusion status, evaluating complex fractures, detecting pseudoarthrosis.
Magnetic Resonance Imaging (MRI)	Superior soft tissue contrast. Visualizes neural elements, discs, ligaments, and tumors [13],[14]	Diagnosing disc herniation, spinal stenosis, spinal cord compression, infection (discitis/osteomyelitis), intradural tumors.
CT Myelography	Defines thecal sac and nerve root compression when MRI is contraindicated. Combines bony (CT) and neural (contrast) detail [20]	Surgical planning in patients with pacemakers or metal implants causing artifact; defining nerve root avulsions.
Bone Scintigraphy (SPECT)	Identifies metabolically active bone lesions (e.g., stress fractures, infection, tumor) [21]	Localizing painful facet joints or sites of pseudoarthrosis for targeted treatment.

The synthesis of information from these modalities enables the surgeon to answer critical questions: What is the exact pathological level and the primary compressing agent? What is the optimal surgical approach (anterior, posterior, lateral, combined)? What is the required extent of decompression? What type and size of implants are needed, and what are their ideal trajectories?[22] This comprehensive preoperative radiological evaluation is, therefore, the indispensable map that guides the entire surgical journey.

Intraoperative Radiological Guidance:

The translation of a preoperative plan into surgical reality presents formidable challenges, primarily due to the spine's complex three-dimensional anatomy, the presence of critical neurovascular structures, and the limited visual field inherent to both open and minimally invasive approaches. Intraoperative radiological guidance has emerged as the solution to this challenge, dramatically enhancing the accuracy, safety, and efficiency of spinal procedures[23]. This guidance spans from simple fluoroscopic verification to sophisticated real-time navigation systems. C-arm fluoroscopy has been the workhorse of intraoperative imaging for decades, providing real-time two-dimensional radiographic views. It is routinely used to confirm the correct surgical level, guide the placement of guidewires and implants, and assess spinal alignment during deformity correction[24] . However, its limitations are significant: it provides only a flattened 2D representation of 3D anatomy, requires repeated irradiation to obtain multiple views (anteroposterior and lateral), and exposes the surgical team to cumulative scatter radiation[25].The evolution towards three-dimensional imaging in the operating room addressed these shortcomings. Intraoperative CT (iCT) scanners, such as the O-arm® system, can acquire volumetric CT data sets with the patient in the surgical position[26]. This 3D dataset can then be used for navigation. In Computer-Assisted Navigation (CAN), the preoperative or intraoperatively acquired 3D images are registered to the patient's anatomy using fiducial markers or a paired-point/surface-matching technique[27]. Surgical instruments, fitted with reflective arrays or electromagnetic sensors, are then tracked in real-time by a camera or field generator. Their precise location and trajectory are superimposed on the multiplanar CT images on a navigation workstation monitor, acting as a GPS for the spine[28]. The impact on pedicle screw placement is profound. Navigation has been shown to significantly improve the accuracy of screw placement, reducing the rate of cortical breaches and malpositioned screws compared to freehand or fluoroscopically-guided techniques[29],[30]. This heightened accuracy directly translates to enhanced patient safety by minimizing the risk of neurological or vascular injury. Furthermore, navigation facilitates the execution of complex trajectories, such as cortical bone trajectory screws or screws in dysmorphic or previously operated anatomy, which would be exceedingly difficult with conventional methods[31]. In the realm of spinal oncology and complex deformity, navigation is transformative. For tumor resections, it allows for precise localization of the lesion, definition of safe resection margins, and avoidance of critical structures.[32] In severe spinal deformities, where normal anatomical landmarks are grossly distorted, navigation provides an unwavering frame of reference for safe instrument placement.[33] The integration of navigation with robotic systems represents the next frontier. Robotic arms, guided by the navigation data, can act as a steady, precise guide for drill sleeves or implant insertion, potentially reducing human tremor and further standardizing technique[34]. Intraoperative MRI (iMRI), though less common due to immense cost and logistical complexity, offers unique advantages for intradural tumor surgery. It allows the surgeon to obtain updated images during the procedure to assess the extent of tumor resection, helping to achieve maximal safe resection before closure[35]. Each modality, from basic fluoroscopy to advanced iMRI, serves to minimizing the discrepancy between surgical plan and execution, making procedures more predictable and outcomes more reliable.

Postoperative Radiological Assessment:

The role of radiology extends decisively beyond the operating room, forming the critical basis for postoperative assessment and long-term patient management. Early and late imaging studies are performed to confirm the technical success of the intervention, monitor the biological process of healing, diagnose complications, and guide further management[36]. The timing and modality of imaging are dictated by the clinical context, the specific procedure performed, and the patient's symptoms. In the immediate postoperative period, plain radiographs are routinely obtained to serve as a new baseline. They confirm the correct placement of hardware (e.g., pedicle screws, cages, rods), verify the restoration of spinal alignment (lordosis, kyphosis, scoliosis correction), and ensure no gross complications such as implant dislodgement or unexpected pneumothorax are present[37].For patients undergoing decompression without fusion, MRI may be performed early if there is a concern for a residual disc fragment, epidural hematoma, or other causes of persistent neural compression[38]. The primary long-term goal of many spinal surgeries, particularly arthrodesis (fusion) procedures, is the achievement of solid bony union. This is a gradual biological process that can take 6 to 24 months. Radiology is the principal tool for assessing fusion status[39]. Follow-up plain films and CT scans are scrutinized for signs of bridging trabecular bone across the grafted segment, the absence of lucent lines around implants (signifying loosening), and the maintenance of alignment[40]. CT is significantly more sensitive and specific than plain radiography for detecting pseudoarthrosis (failed fusion), as it can visualize subtle bony bridging that may be obscured on an X-ray[41].

Table 2: Common Postoperative Complications and Their Radiologic Hallmarks

Complication	Typical Timeframe	Key Radiologic Findings (Modality)
Implant Malposition/Failure	Early or late	Screw breach of pedicle cortex (CT), screw/rod fracture or bending (X-ray/CT), cage migration/subsidence (X-ray/CT) [29],[37].
Pseudoarthrosis	Late (>6-12 months)	Absence of bridging bone across disc space/facet joints, progressive lucency around implants, implant failure (X-ray, CT). CT is gold standard[40],[41].
Adjacent Segment Disease	Late (months to years)	New disc degeneration, stenosis, instability, or spondylolisthesis at levels adjacent to a fusion construct (X-ray, MRI)[18].
Recurrent Disc Herniation	Variable	Re-appearance of disc material in the spinal canal at the operated level, often distinguishable from postoperative scar by contrast-enhanced MRI[38].
Epidural Fibrosis/Scar	Late	Enhancing soft tissue in the surgical bed on contrast MRI, typically enveloping rather than displacing the thecal sac[38].
Surgical Site Infection	Early or delayed	Discitis/osteomyelitis: bone marrow edema, endplate erosion, paraspinal fluid/abscess (MRI, CT). Loosening of hardware may be seen[14].
Neurological Injury/CSF Leak	Early	MRI may show cord signal change (edema, contusion) or a pseudomeningocele (fluid collection communicating with thecal sac) [38].

Furthermore, imaging is vital for diagnosing complications that may arise over time. Adjacent segment disease, the accelerated degeneration of spinal segments next to a fusion, is evaluated with dynamic radiographs and MRI to assess for new instability or stenosis[38]. Symptomatic hardware failure, such as screw breakage or rod fracture, is readily apparent on X-ray or CT. Infection, though a clinical diagnosis, is supported by imaging findings like osteomyelitis, fluid collections, or implant loosening on MRI or CT[14]. In cases of persistent or new radicular pain, contrast-enhanced MRI is the modality of choice to differentiate between recurrent disc herniation (which typically does not enhance centrally) and postoperative epidural fibrosis (which enhances homogenously)[38]. Thus, postoperative radiology functions as the surgeon's eyes into the healing spine, providing objective data to confirm success, explain failure, and guide decisions on rehabilitation, intervention, or revision surgery.

Challenges and Limitations:

Despite its transformative benefits, the integration of advanced radiology into spinal surgery is not without significant challenges, limitations, and trade-offs. Acknowledging these is essential for balanced clinical application and for directing future technological improvements.

A primary and pervasive concern is radiation exposure. This is a dual burden affecting both the patient and the surgical team. Procedures reliant heavily on intraoperative fluoroscopy, particularly complex deformity corrections and percutaneous techniques, can involve prolonged fluoroscopy time, leading to considerable patient exposure[25]. More critically, the operating surgeon and staff, who are present for hundreds of such procedures annually, face a cumulative lifetime risk of scatter radiation exposure, with associated concerns for cataracts, malignancy, and other stochastic effects. While 3D navigation systems like iCT can reduce the need for continuous fluoroscopy, they themselves deliver a substantial dose per acquisition, and the trade-off between reduced fluoro-time and a higher-dose 3D scan must be considered[26]. Strategies like ALARA (As Low As Reasonably Achievable) principles, protective shielding, and the use of radiation-sparing navigation technologies are imperative[25].

Cost and Resource Intensity present another major hurdle. Advanced imaging equipment (high-field MRI, intraoperative CT/O-arm, navigation systems, robotic platforms) represents a multi-million-dollar capital investment. Their maintenance, software updates, and the need for specialized technical personnel add substantial ongoing operational costs[34]. This economic barrier can limit access to these technologies, potentially creating disparities in care between high-resource and low-resource settings. The cost-benefit analysis, while often favorable in terms of reduced revision rates and complications, requires careful institutional consideration.

Technical and Logistical Limitations also exist. Metal artifact from implanted hardware can severely degrade image quality on both CT and, especially, MRI, obscuring critical anatomy and complicating the assessment of fusion or recurrent pathology[16]. While metal artifact reduction sequences (MARS) in MRI and iterative reconstruction algorithms in CT have improved this, it remains a challenge. The process of image registration for navigation, if not performed detailedly, can introduce error, leading to a dangerous mismatch between the virtual image and the real patient anatomy ("navigation drift")[27]. This necessitates continuous surgical vigilance and correlation with anatomical landmarks. The physical footprint and workflow integration of intraoperative scanners can also disrupt operating room logistics and prolong anesthesia time.

Finally, there is the risk of Over-reliance and Diminished Surgical Acumen. There is a valid concern that excessive dependence on imaging technology could potentially erode a surgeon's fundamental knowledge of spinal anatomy and tactile, hands-on surgical skills. Imaging should augment, not replace, surgical judgment and mastery of anatomy. A misplaced trust in navigation data without clinical correlation can be as hazardous as having no guidance at all. Furthermore, not all pathologies or surgical steps are image-definable; the decision-making regarding the extent of neural decompression, for instance, often relies on direct visual and physiological feedback (e.g., dural pulsation, nerve mobility) that imaging cannot provide. Thus, the radiologic approach is a powerful tool that must be wielded by a skilled and critically thinking surgeon, not a substitute for one.

CONCLUSION

The evolution of spinal surgery from a high-risk endeavor to a precise discipline has been guided by the parallel advancement of medical radiology. As detailed, radiology is the central nervous system of the modern surgical workflow. Preoperatively, it provides essential diagnosis and anatomical roadmaps. Intraoperatively, it acts as a dynamic guide for real-time navigation. Postoperatively, it objectively assesses healing and complications. The synergy between surgical skill and imaging expertise is paramount. While challenges regarding radiation, cost, and technical limits remain, the trajectory is clear. Future advancements like AI, augmented reality, and improved imaging protocols will further refine this partnership. Ultimately, radiology is the critical catalyst that elevates spinal surgery from an artful craft to a sophisticated science, directly improving patient outcomes and the management of a vital structural system. Nevertheless, the effective integration of radiology depends on appropriate patient selection, institutional resources, and surgical expertise.

DECLARATIONS

Ethics Approval and Consent to Participate
Not Applicable.

Consent for Publication
Not Applicable.

Funding
None.

Competing Interests
None.

Authors' Contributions

All authors made substantial contributions to this work. All participated in the conceptualization, literature review, and critical discussion of the manuscript's intellectual content. Each author was involved in drafting or critically revising the work and approved the final version for publication. The corresponding author, coordinated the collaboration and manuscript preparation.

Acknowledgements
None.

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