THE ROLE OF IMAGING IN SPINAL TRAUMA MANAGEMENT: A COMPREHENSIVE NARRATIVE REVIEW OF IMAGING MODALITIES AND CLINICAL IMPACT

Abdulmajeed Dhaher Mushref Alshehri[1]*, Abdullah Mohamed Ali Alshehri[1], Fahad Gorman Abdullah Alshehri[1], Mohamed Gorman Ali Alshehri[1], Abdulrahman Awad Alshehri[1]

Abstract

Imaging modalities play a crucial role in the comprehensive management of spinal trauma, offering detailed insights into bony structures, soft tissue involvement, neurological status, and functional outcomes. This narrative review explores the diverse array of imaging modalities utilized in spinal trauma assessment, including radiography, computed tomography (CT), magnetic resonance imaging (MRI), nuclear medicine techniques, ultrasound, and emerging technologies. Each modality's strengths, limitations, and clinical applications are examined, emphasizing their contributions to diagnosis, treatment planning, surgical interventions, and long-term monitoring.

The review delineates the anatomy and pathophysiology of spinal trauma, highlighting mechanisms of injury, classification systems, and injury patterns. Clinical applications of imaging in spinal trauma management, such as diagnosis and classification of spinal injuries, preoperative planning, monitoring, and imaging-guided interventions, are thoroughly discussed. Additionally, the role of imaging algorithms, multidisciplinary approaches, and artificial intelligence (AI) applications in decision-making processes is explored.

Future directions in spinal trauma imaging, including advances in technology, AI-driven innovations, and research needs, are considered, offering insights into potential enhancements in diagnostic accuracy, workflow efficiencies, and personalized care pathways. Overall, this review underscores the critical importance of integrating imaging findings into multidisciplinary protocols, trauma algorithms, and clinical decision-making processes to optimize patient outcomes in spinal trauma management.

Keywords: spinal trauma, imaging modalities, radiography, computed tomography, magnetic resonance imaging, nuclear medicine, ultrasound, multidisciplinary approach, artificial intelligence, clinical decision-making.

[1]*Radiology Department, Al-Namas General Hospital, Al-Namas, Saudi Arabia

***Corresponding Author:** Abdulmajeed Dhaher Mushref Alshehri
*Radiology Department, Al-Namas General Hospital, Al-Namas, Saudi Arabia

DOI: 10.53555/ecb/2022.11.5.085

I. Introduction

Imaging plays a pivotal role in the comprehensive management of spinal trauma, facilitating accurate diagnosis, treatment planning, and prognostication [1]. Spinal trauma encompasses a spectrum of injuries ranging from mild sprains to severe fractures and spinal cord damage, often resulting from vehicular accidents, falls, sports injuries, or violent trauma. The complex anatomy of the spine, comprising vertebrae, intervertebral discs, spinal cord, and supporting ligaments, necessitates advanced imaging techniques for thorough assessment [2,3].

Traditional imaging methods such as plain radiography have long been fundamental in evaluating bony structures and initial assessments of spinal injuries. However, advancements in imaging modalities, including computed tomography (CT), magnetic resonance imaging (MRI), and nuclear medicine techniques, have revolutionized the diagnostic landscape of spinal trauma [4]. These modalities provide detailed information not only about bony injuries but also soft tissue involvement, spinal cord compression, and vascular compromise, enabling clinicians to formulate tailored management strategies [3].

The significance of imaging in spinal trauma extends beyond mere diagnosis; it guides surgical interventions, aids in prognostication, and contributes to long-term monitoring of patients. Moreover, with the advent of artificial intelligence (AI) and machine learning algorithms, imaging interpretation has become more efficient, leading to quicker diagnosis and improved patient outcomes. Therefore, a comprehensive review of imaging modalities and their clinical impact in spinal trauma management is essential to delineate current practices, identify areas for improvement, and guide future research endeavors [2-4].

II. Anatomy and Pathophysiology of Spinal Trauma

The spine is a complex structure comprising vertebrae, intervertebral discs, spinal cord, nerves, and surrounding ligaments and muscles. Its primary functions include providing structural support, facilitating movement, protecting the spinal cord, and transmitting neural signals [5]. The spinal column is divided into distinct regions: cervical (C1-C7), thoracic (T1-T12), lumbar (L1-L5), sacral, and coccygeal segments. Each segment has unique anatomical features and biomechanical properties, influencing the patterns and severity of spinal injuries [5,6].

Spinal trauma can result from various mechanisms, including axial loading (e.g., falls from height), flexion-extension forces (e.g., whiplash injuries), rotational forces (e.g., twisting injuries), and direct impact (e.g., motor vehicle collisions). These mechanisms can lead to different types of injuries such as fractures, dislocations, ligamentous injuries, and spinal cord compression [7]. The severity of trauma depends on factors such as the magnitude of force, direction of impact, pre-existing spinal conditions, and patient age and health status [8,9].

Spinal injuries are classified based on various criteria, including anatomical location, severity, mechanism of injury, and neurological involvement [10-12]. Common classifications include:

1. **Vertebral Fractures:** Classified based on the Denis classification system (type I-III) or by specific anatomical regions (e.g., odontoid fractures, burst fractures).
2. **Spinal Cord Injuries (SCI):** Classified according to the American Spinal Injury Association (ASIA) impairment scale, ranging from complete (ASIA A) to incomplete (ASIA B-D) injuries.
3. **Ligamentous Injuries:** Categorized based on the affected ligaments (e.g., anterior cruciate ligament [ACL], posterior cruciate ligament [PCL], spinal ligaments).
4. **Dislocations and Subluxations:** Described by the direction and degree of displacement (e.g., anterior/posterior, lateral dislocations).
5. **Neurological Injury Patterns:** Including central cord syndrome, Brown-Sequard syndrome, anterior cord syndrome, and cauda equina syndrome.

Understanding these classifications is crucial for accurate diagnosis, treatment planning, and prognostication in spinal trauma management. Imaging modalities play a key role in confirming and characterizing these injuries, guiding appropriate interventions and optimizing patient outcomes [12,13].

III. Imaging Modalities in Spinal Trauma

A. Radiography

Radiography remains a cornerstone in the initial assessment of spinal trauma due to its widespread availability, cost-effectiveness, and ability to visualize bony structures. Plain radiography, including anteroposterior (AP), lateral, and oblique views, provides valuable information regarding vertebral alignment, fractures, dislocations, and spinal stability [14]. Advanced radiographic techniques such as flexion-extension views are particularly useful in evaluating spinal instability and assessing the range of motion, aiding in the diagnosis of ligamentous injuries and degenerative conditions [10,15].

B. Computed Tomography (CT)

CT imaging has revolutionized the evaluation of spinal trauma by offering high-resolution, cross-sectional images of bony structures with exceptional detail [15]. Multi-Detector CT (MDCT) scanners allow rapid acquisition of multiple slices, facilitating 3D reconstructions and precise delineation of fractures, spinal canal compromise, and intra-articular injuries. CT angiography (CTA) is utilized to assess vascular injuries, including vertebral artery dissections or traumatic pseudoaneurysms, which are crucial considerations in spinal trauma management [14,15].

C. Magnetic Resonance Imaging (MRI)

MRI is indispensable in the assessment of soft tissue structures, including the spinal cord, intervertebral discs, ligaments, and neural elements. Conventional MRI sequences such as T1-weighted, T2-weighted, and STIR (Short Tau Inversion Recovery) sequences provide detailed anatomical information and help identify spinal cord compression, disc herniations, and ligamentous injuries [16]. Advanced MRI techniques such as diffusion-weighted imaging (DWI) and functional MRI (fMRI) offer insights into tissue microstructure, perfusion, and neural activity, aiding in the evaluation of spinal cord integrity and functional outcomes [14-17].

D. Nuclear Medicine Imaging

Nuclear medicine imaging modalities play a complementary role in spinal trauma evaluation, particularly in detecting subtle bone injuries and assessing skeletal metabolism [18]. Bone scintigraphy utilizing radiopharmaceuticals like technetium-99m (Tc-99m) can detect early changes indicative of occult fractures or bone marrow abnormalities. Single-photon emission computed tomography (SPECT) provides functional and metabolic information, aiding in the localization of spinal lesions and evaluation of spinal fusion integrity in postoperative cases [18,19].

E. Ultrasound

While less commonly used in spinal trauma imaging, ultrasound may have specific applications, particularly in pediatric patients or when assessing soft tissue injuries, such as hematoma or abscess formation. Ultrasound-guided interventions, such as facet joint injections or nerve blocks, also play a role in pain management strategies for spinal trauma patients [14,15].

F. Emerging Imaging Technologies

Advances in imaging technologies continue to expand the armamentarium for spinal trauma evaluation. Three-dimensional (3D) imaging techniques offer enhanced visualization of complex spinal anatomy, aiding in surgical planning and patient education [8,14]. Artificial intelligence (AI) applications, including computer-aided detection and image segmentation algorithms, show promise in improving diagnostic accuracy, reducing interpretation times, and optimizing resource utilization in spinal trauma imaging [10,15,16].

IV. Clinical Applications and Impact of Imaging in Spinal Trauma Management

A. Diagnosis and Classification of Spinal Injuries

Imaging plays a pivotal role in the accurate diagnosis and classification of spinal injuries, guiding treatment decisions and prognostication. For spinal cord injuries (SCI), MRI is crucial in determining the extent and level of cord compression, identifying associated injuries such as epidural hematomas or ligamentous disruptions, and assessing the degree of neurological compromise using ASIA impairment scale criteria [20,21]. Vertebral fractures and dislocations are meticulously evaluated using radiography and CT imaging, aiding in the classification based on severity, stability, and associated soft tissue injuries [21].

B. Preoperative Planning

Imaging modalities provide essential information for preoperative planning in spinal trauma cases. CT scans with 3D reconstructions assist surgeons in visualizing fracture patterns, assessing spinal alignment, and planning instrumentation strategies for spinal stabilization procedures. MRI helps identify any neural tissue compromise, plan decompressive surgeries, and evaluate the feasibility of minimally invasive approaches [5,11,22].

C. Monitoring and Follow-up of Spinal Trauma Patients

Postoperative and follow-up imaging are critical in monitoring spinal trauma patients for complications, assessing healing trajectories, and evaluating treatment efficacy. Serial radiographs, CT scans, and MRI studies track fracture healing, spinal fusion integrity, and resolution of soft tissue injuries over time, guiding rehabilitation protocols and determining patient readiness for activity progression [22,23].

D. Complications and Pitfalls in Imaging Interpretation

Despite the advancements in imaging modalities, certain pitfalls and limitations exist in interpretation. These include artifact-related challenges, such as metallic hardware interference on MRI or beam-hardening artifacts on CT scans, which may obscure critical findings [24]. Awareness of these limitations and correlation with clinical findings are essential to avoid misinterpretation and ensure accurate diagnosis and treatment planning [25].

E. Imaging-Guided Interventions in Spinal Trauma

Imaging plays a vital role in guiding minimally invasive interventions for pain management and spinal stabilization. Fluoroscopy-guided procedures, such as facet joint injections, epidural steroid injections, and vertebral augmentation techniques (e.g., vertebroplasty, kyphoplasty), rely on imaging guidance for accurate needle placement and therapeutic efficacy assessment [9,12,22,23].

V. Integrating Imaging Findings into Spinal Trauma Management Protocols

A. Multidisciplinary Approach

Effective spinal trauma management necessitates a multidisciplinary approach involving collaboration among various healthcare professionals, including radiologists, neurosurgeons, orthopedic surgeons, neurologists, physiatrists, and rehabilitation specialists. Each member of the team contributes unique expertise and perspectives to the comprehensive evaluation and treatment of spinal injuries [25,26]. Radiologists play a central role in interpreting imaging studies, providing detailed reports, and communicating findings to the treating clinicians. Neurosurgeons and orthopedic surgeons rely on imaging data for surgical planning, guiding interventions, and ensuring optimal patient outcomes [4,7]. Neurologists and physiatrists utilize imaging findings to assess neurological status, monitor recovery trajectories, and tailor rehabilitation strategies. Rehabilitation specialists coordinate comprehensive care plans, incorporating imaging information to guide functional assessments, mobility goals, and long-term management strategies. A cohesive multidisciplinary approach ensures holistic patient care, promotes optimal functional outcomes, and minimizes complications in spinal trauma management [20,27].

B. Imaging Algorithms in Trauma Settings

Imaging algorithms are integral components of trauma protocols designed to streamline diagnostic pathways, prioritize imaging modalities, and optimize resource utilization in acute care settings. These algorithms are tailored to specific clinical scenarios, injury patterns, and patient presentations, guiding clinicians in selecting the most appropriate imaging studies based on urgency, suspected injuries, and potential complications [5,9,18]. For example, trauma protocols may delineate imaging algorithms for suspected spinal cord injuries, emphasizing the sequential use of radiography, CT scans, and MRI studies based on initial clinical assessments and neurological findings. Similarly, algorithms for suspected vertebral fractures may outline the role of radiography for initial screening, followed by CT imaging for detailed fracture characterization and surgical planning when indicated. Imaging algorithms enhance efficiency, reduce unnecessary imaging studies, and expedite timely interventions, optimizing patient care in trauma settings [28,29].

C. Role of Imaging in Decision-Making and Treatment Planning

Imaging plays a pivotal role in decision-making and treatment planning across all phases of spinal trauma management. In the acute setting, rapid interpretation of imaging studies guides immediate interventions, such as spinal stabilization procedures, decompressive surgeries, or neuroprotective measures for spinal cord injuries [1,4,16]. Imaging findings inform the selection of appropriate surgical techniques, instrumentation options, and fusion strategies, ensuring optimal spinal alignment, stability, and neurological preservation. Moreover, imaging-guided interventions, including fluoroscopy-guided injections, nerve blocks, and minimally invasive procedures, offer targeted pain management solutions and facilitate functional recovery. Longitudinal imaging assessments during follow-up appointments aid in monitoring healing trajectories, assessing treatment efficacy, and modifying management strategies as needed [29,30]. The integration of imaging data into decision-making processes enhances precision, reduces complications, and improves outcomes in spinal trauma patients [30].

VI. Conclusion

In conclusion, imaging modalities play a pivotal role in the comprehensive management of spinal trauma, providing crucial information for diagnosis, treatment planning, and monitoring.

Radiography, CT, MRI, nuclear medicine techniques, ultrasound, and emerging imaging technologies offer complementary strengths in assessing bony integrity, soft tissue involvement, neurological status, and functional outcomes. The integration of imaging findings into multidisciplinary protocols, trauma algorithms, and clinical decision-making processes enhances precision, guides interventions, and improves patient outcomes. Future directions in spinal trauma imaging, including advances in technology, AI applications, and research initiatives, hold promise for further enhancing diagnostic accuracy, streamlining workflows, and advancing personalized care in spinal trauma management. The insights gained from this comprehensive review underscore the importance of continued education, interdisciplinary collaboration, and evidence-based practices in spinal trauma imaging. Clinicians, radiologists, and researchers must remain vigilant in adopting emerging technologies, validating AI-driven solutions, and addressing research needs to optimize imaging protocols, enhance diagnostic capabilities, and improve patient outcomes. By leveraging the synergistic potential of imaging technologies, AI innovations, and multidisciplinary approaches, we can continue to advance the field of spinal trauma imaging, transform clinical practices, and ultimately improve the lives of patients affected by spinal injuries.

VII. References

1. Kumar Y, Hayashi D. Role of magnetic resonance imaging in acute spinal trauma: a pictorial review. BMC musculoskeletal disorders. 2016 Dec;17:1-1.
2. Rajasekaran S, Kanna RM, Shetty AP. Management of thoracolumbar spine trauma: An overview. Indian journal of orthopaedics. 2015 Feb;49(1):72-82.
3. Rajasekaran S, Vaccaro AR, Kanna RM, Schroeder GD, Oner FC, Vialle L, Chapman J, Dvorak M, Fehlings M, Shetty AP, Schnake K. The value of CT and MRI in the classification and surgical decision-making among spine surgeons in thoracolumbar spinal injuries. European Spine Journal. 2017 May;26:1463-9.
4. Eckert MJ, Martin MJ. Trauma: spinal cord injury. Surgical Clinics. 2017 Oct 1;97(5):1031-45.
5. Neal JM, Kopp SL, Pasternak JJ, Lanier WL, Rathmell JP. Anatomy and pathophysiology of spinal cord injury associated with regional anesthesia and pain medicine: 2015 update. Regional Anesthesia & Pain Medicine. 2015 Sep 1;40(5):506-25.
6. Mataliotakis GI, Tsirikos AI. Spinal cord trauma: pathophysiology, classification of spinal cord injury syndromes, treatment principles and controversies. Orthopaedics and Trauma. 2016 Oct 1;30(5):440-9.
7. Quadri SA, Farooqui M, Ikram A, Zafar A, Khan MA, Suriya SS, Claus CF, Fiani B, Rahman M, Ramachandran A, Armstrong II. Recent update on basic mechanisms of spinal cord injury. Neurosurgical Review. 2020 Apr;43:425-41.
8. Alizadeh A, Dyck SM, Karimi-Abdolrezaee S. Traumatic spinal cord injury: an overview of pathophysiology, models and acute injury mechanisms. Frontiers in neurology. 2019 Mar 22;10:441408.
9. Eli I, Lerner DP, Ghogawala Z. Acute traumatic spinal cord injury. Neurologic Clinics. 2021 May 1;39(2):471-88.
10. Vaccaro AR, Schroeder GD, Kepler CK, Cumhur Oner F, Vialle LR, Kandziora F, Koerner JD, Kurd MF, Reinhold M, Schnake KJ, Chapman J. The surgical algorithm for the AOSpine thoracolumbar spine injury classification system. European Spine Journal. 2016 Apr;25:1087-94.
11. Vaccaro AR, Koerner JD, Radcliff KE, Oner FC, Reinhold M, Schnake KJ, Kandziora F, Fehlings MG, Dvorak MF, Aarabi B, Rajasekaran S. AOSpine subaxial cervical spine injury classification system. European spine journal. 2016 Jul;25:2173-84.
12. Rajasekaran S, Vaccaro AR, Kanna RM, Schroeder GD, Oner FC, Vialle L, Chapman J, Dvorak M, Fehlings M, Shetty AP, Schnake K. The value of CT and MRI in the classification and surgical decision-making among spine surgeons in thoracolumbar spinal injuries. European Spine Journal. 2017 May;26:1463-9.
13. Kepler CK, Vaccaro AR, Koerner JD, Dvorak MF, Kandziora F, Rajasekaran S, Aarabi B, Vialle LR, Fehlings MG, Schroeder GD, Reinhold M. Reliability analysis of the AOSpine thoracolumbar spine injury classification system by a worldwide group of naïve spinal surgeons. European spine journal. 2016 Apr;25:1082-6.
14. Shah LM, Ross JS. Imaging of spine trauma. Neurosurgery. 2016 Nov 1;79(5):626-42.
15. Izzo R, Popolizio T, Balzano RF, Pennelli AM, Simeone A, Muto M. Imaging of cervical spine traumas. European journal of radiology. 2019 Aug 1;117:75-88.

16. Kumar Y, Hayashi D. Role of magnetic resonance imaging in acute spinal trauma: a pictorial review. BMC musculoskeletal disorders. 2016 Dec;17:1-1.
17. van Den Hauwe L, Sundgren PC, Flanders AE. Spinal trauma and spinal cord injury (SCI). Diseases of the Brain, Head and Neck, Spine 2020–2023: Diagnostic Imaging. 2020:231-40.
18. McAllister AS, Nagaraj U, Radhakrishnan R. Emergent imaging of pediatric cervical spine trauma. Radiographics. 2019 Jul;39(4):1126-42.
19. Govaert GA, IJpma FF, McNally M, McNally E, Reininga IH, Glaudemans AW. Accuracy of diagnostic imaging modalities for peripheral post-traumatic osteomyelitis–a systematic review of the recent literature. European journal of nuclear medicine and molecular imaging. 2017 Aug;44:1393-407.
20. Yelamarthy PK, Chhabra HS, Vaksha V, Agarwal Y, Agarwal A, Das K, Erli HJ, Bapat M, Singh R, Gautam D, Tandon R. Radiological protocol in spinal trauma: literature review and Spinal Cord Society position statement. European Spine Journal. 2020 Jun;29:1197-211.
21. Freund P, Seif M, Weiskopf N, Friston K, Fehlings MG, Thompson AJ, Curt A. MRI in traumatic spinal cord injury: from clinical assessment to neuroimaging biomarkers. The Lancet Neurology. 2019 Dec 1;18(12):1123-35.
22. David G, Mohammadi S, Martin AR, Cohen-Adad J, Weiskopf N, Thompson A, Freund P. Traumatic and nontraumatic spinal cord injury: pathological insights from neuroimaging. Nature Reviews Neurology. 2019 Dec;15(12):718-31.
23. Karsy M, Hawryluk G. Modern medical management of spinal cord injury. Current Neurology and Neuroscience Reports. 2019 Sep;19:1-7.
24. Copley PC, Tilliridou V, Kirby A, Jones J, Kandasamy J. Management of cervical spine trauma in children. European Journal of Trauma and Emergency Surgery. 2019 Oct;45:777-89.
25. Rouanet C, Reges D, Rocha E, Gagliardi V, Silva GS. Traumatic spinal cord injury: current concepts and treatment update. Arquivos de neuro-psiquiatria. 2017;75:387-93.
26. Shank CD, Walters BC, Hadley MN. Current topics in the management of acute traumatic spinal cord injury. Neurocritical care. 2019 Apr 15;30:261-71.
27. Inaba K, Byerly S, Bush LD, Martin MJ, Martin DT, Peck KA, Barmparas G, Bradley MJ, Hazelton JP, Coimbra R, Choudhry AJ. Cervical spinal clearance: a prospective Western Trauma Association multi-institutional trial. Journal of Trauma and Acute Care Surgery. 2016 Dec 1;81(6):1122-30.
28. Hu CK, Chen MH, Wang YH, Sun JS, Wu CY. Integration of multiple prognostic predictors in a porcine spinal cord injury model: A further step closer to reality. Frontiers in Neurology. 2023 Mar 8;14:1136267.
29. Farhadi HF, Kukreja S, Minnema A, Vatti L, Gopinath M, Prevedello L, Chen C, Xiang H, Schwab JM. Impact of admission imaging findings on neurological outcomes in acute cervical traumatic spinal cord injury. Journal of neurotrauma. 2018 Jun 15;35(12):1398-406.
30. Ahuja CS, Schroeder GD, Vaccaro AR, Fehlings MG. Spinal cord injury—what are the controversies?. Journal of orthopaedic trauma. 2017 Sep 1;31:S7-13.