Spinal Trauma and Spinal Cord Injury

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Introduction

The majority of the spinal injuries (60 %) affect young healthy males between 15 and 35 years of age with cervical spine injuries to be most common. The main cause for spinal injuries is blunt trauma most commonly due to motor vehicle accidents (48 %), followed by falls (21 %), and sport injuries (14.6 %). Assault and penetrating trauma account for approximately 10–20 % of the cases. Injuries to the spinal column and the spinal cord are a major cause of disability, affecting predominately young healthy individuals with important socioeconomic consequences, and the costs of lifetime care and rehabilitation exceed one million US dollars per patient excluding financial losses related to wages and productivity. Over the past several decades, the mean age of the spinal cord-injured patient has increased which is attributed to a substantially greater proportion of injuries related to falls in the elderly.

Cervical spine injuries, of which approximately one-third occur in the craniocervical junction (CCJ) [1], account for the majority of the spinal injuries followed by thoracolumbar fractures diagnosed. Almost half of the spinal injuries result in neurological deficits, often severe and sometimes fatal [2]. Survival is inversely related to the patient's age and neurological level of injury, with lower overall survival for high quadriplegic patients compared to paraplegic injuries. Mortality rate during the initial hospitalization is reported to be almost 10 % [3].

Injury to the spinal cord occurs in 10–14 % of spinal fractures and dislocations with injuries of the cervical spine being by far the most common cause of neurological deficits (40 % of cervical injuries) [4, 5]. The majority of injuries to the spinal cord (85 %) occur at the time of trauma, whereas 5–10 % of injuries to the spinal cord occur in the immediate post-injury period [6].

The imaging methods for evaluating patients with acute spinal trauma have dramatically changed in the last decade especially with the development of more advanced computed tomography (CT) scanner such as the use of thin-section multi-detector computed tomography (MDCT) that with sagittal and coronal reformats allows for the evaluation of extent of the injury of the spinal column. In addition, magnetic resonance imaging (MRI) has become the method of choice for evaluation of spinal cord, soft tissue, and ligamentous injury or when a reliable neurological examination cannot be performed.

Imaging Modalities

In the emergency setting, one of the critical decisions to make is determining which patients require imaging of the spine and/or cord and what type of imaging is required. The appropriate selection of imaging depends upon several factors such as availability of the different imaging modalities, the patient's clinical and neurological condition, type of trauma (blunt, single, or multi-trauma), and other associated injuries to the brain, thorax, or abdomen. Clinical factors to consider also include the quality and severity of pain, limitations in motion, or the presence of permanent or transient neurological deficits. MRI is reserved for those patients with post-traumatic myelopathy (spinal cord dysfunction) or in the instance whereupon a patient's symptoms cannot be explained by findings on plain films or CT and when a reliable neurological exam cannot be obtained.

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J. Hodler et al. (eds.), *Diseases of the Brain, Head and Neck, Spine 2016–2019: Diagnostic Imaging*, DOI 10.1007/978-3-319-30081-8_21

Plain-Film Radiography

In the rare circumstance where MDCT is not available, the initial imaging modality is radiography. A minimum of three set of views must be obtained: lateral, anteroposterior, and an open-mouth odontoid view to clear the cervical spine. Often additional views such as oblique views and/or the swimmer's view are performed in an attempt to clear the cervicothoracic junction. With the exception of pediatric trauma, in most settings, radiography has been supplanted by MDCT.

Computed Tomography (CT)

Thin-section multi-detector computed tomography (MDCT) is the initial method of choice when evaluating the cervical spine for bone injuries after blunt trauma allowing for whole-spine examination in a very short time, and fast reformatting of images in multiple planes allows for better and more exact diagnosis of bone and soft tissue abnormalities [7–13]. Moreover in the instance of polytrauma, spine images can be reconstructed directly from the chest, abdomen, and pelvis datasets with sensitivity that is equivalent to a dedicated CT study. This has the added benefit of minimizing radiation dose.

With the introduction of these new MDCT imaging techniques, most trauma centers have set up dedicated acute (multi-)trauma protocol(s) which include CT of the brain, cervical spine, thorax and abdomen, and pelvis, with subsequent reformatting of images of the thoracic and lumbar spine. This both expedites the data acquisition for medically unstable patients and serves to minimize radiation dose since the body imaging data can be reconstructed offline into targeted spine reconstructions. CT has a higher sensitivity to fractures (especially involving the posterior elements) than radiography. This rapid digital assessment of the spinal axis has been shown to be more efficient and safer by virtually eliminating the need for repeat radiographs and unnecessary patient transfers in the setting of an unstable spine. Moreover, the diagnostic quality of radiography varies considerably, is more time-consuming to acquire, and may be difficult to perform in a medically unstable patient. While MDCT excels at delineating bony injury, it also can detect many soft tissue abnormalities such as disc herniation, paravertebral soft tissue, and epidural hematoma. A high-resolution CT imaging protocol begins with submillimeter overlapping partitions to create an isotropic dataset that yields identical spatial resolution in any reconstructed plane. Axial data can be reformatted into thicker sections for diagnostic display, with reformatted 1.25–2-mm thin slices in the C1–C2 region, 2–3-mm thin slices in the rest of the cervical spine, and 3–4-mm thin slices in the thoracic and lumbar spine that are typically chosen for axial presentation. Reformatted sagittal and coronal images of the entire spine are produced from contiguous submillimeter (0.3–0.75 mm) axial images or, on the older scanners, from thicker slices that have been reconstructed with overlapping (e.g., at 1.5 mm). Multiplanar reformatted (MPR) sagittal and coronal images of the entire spine are typically produced automatically from the scanning console or from a nearby workstation. Reconstructions are performed with both bone and soft tissue algorithms.

Magnetic Resonance Imaging (MRI)

The greatest impact that MRI has made in the evaluation of spinal trauma has been in assessment of the soft tissue component of injury. MRI is today considered the method of choice for assessing the spectrum of soft tissue injuries associated with spinal trauma. This includes damage to the intervertebral discs, ligaments, vascular structures, and spinal cord [14–16]. No other imaging modality has been able to faithfully reproduce the internal architecture of the spinal cord, and it is this particular feature that is unique to MRI. Any patient who has a persistent neurological deficit after spinal trauma should undergo an MRI in the acute period to exclude direct damage/compression to the spinal cord. MRI provides unequivocal evidence of not only spinal cord injury but will also reliably demonstrate disc injuries/herniations, paraspinal soft tissue edema (ligament strain/failure), epidural hematomas, and vascular injury. In addition, MRI provides the most reliable assessment of chronic spinal cord injury and the imaging analogs of post-traumatic progressive myelopathy (PTPM) which is often manifested with imaging as syrinx formation, myelomalacia, and cord atrophy (Fig. 1). The extent with which MRI is able to determine spinal instability is overstated as MRI is unable to provide a reliable assessment of ligamentous integrity in most cases. In fact, MRI falsely overestimates the soft tissue component of injury.

An acute spinal trauma MR imaging protocol of the cervical spine shall include 3-mm thick sagittal T1- (T1W) and T2-weighted (T2W) and short tau inversion recovery (STIR) sequences and 3-mm thick axial T2*- weighted gradient recalled echo (GRE) images without contrast. In the thoracic and lumbar spine, 4-mm thick sagittal T1W, T2W, and STIR sequences and axial 4-mm thick T1W, T2W, and T2*GRE images without contrast are recommended. 3D volumetric axial GRE or T2-weighted partitions at 1–2-mm thickness are useful in the cervical region. Fat-saturated T2W images are valuable to evaluate for ligamentous and soft tissue injuries and T2* GRE to evaluate for small hemorrhage or blood products in the spinal cord.

Fig. 1 Post-traumatic syringomyelia. There is a large cystic cavity located within the lower cervical spinal cord extending into the upper thoracic spine

Different Grading Systems to Evaluate Spinal Injuries

There are different classic grading scales for determining spinal instability of thoracolumbar injuries based upon the McAfee (two column) and Denis three-column concept [17, 18], which relies only on CT findings of the Magerl classification [19]. In recent years a new grading scale that is based on CT and magnetic resonance (MR) imaging findings, like the thoracolumbar injury classification and severity score (TLICS), has been developed by the Spine Trauma Group [20] to overcome some of the perceived difficulties regarding the use of other thoracolumbar spinal fracture classification systems for determining treatment. Also for the grading of the cervical spine, a new grading scale and score system – the cervical spine Subaxial Injury Classification and Scoring (SLIC) system [21] – has been developed and is gaining acceptance among spine surgeons.

Injuries to the Vertebral Column

Classically, injuries to the spinal column are categorized by mechanism of injury and/or by instability. *Instability* is defined by White and Punjabi as abnormal translation between adjacent vertebral segments with normal physiologic motion. Unrecognized instability after trauma is a potential cause of delayed spinal cord injury. This is why early stabilization of the initial injury is an imperative to appropriate clinical management. The simplest method to test for instability in a controlled environment is by performing flexion and extension lateral radiography to produce a visible subluxation at a suspected level.

From an imaging point of view and for the evaluation of the thoracolumbar spine, the spine can be divided into three osteo-ligamentous columns: anterior, middle, and posterior column [17]. The anterior column includes the anterior longitudinal ligament and anterior two-thirds of the vertebral body and disc including annulus fibrosus. The middle column is composed of the posterior third of the vertebral body and disc including annulus fibrosus and posterior longitudinal ligament. Finally, the posterior column is composed of the pedicles, articular processes, facet capsules, laminae, ligamenta flava, spinous processes, and the interspinous ligaments. The mechanism of injury will result in several different types of traumatic injuries to the cervical, thoracic, and lumbar vertebral column and spinal cord, which may result in stable or unstable spine injuries. Although this model is often inferred for cervical injuries, there is no similar established model in the cervical spine.

Because of the distinct anatomic differences and the resultant injury patterns, injuries to the cervical spine are divided into subaxial injuries (cranial base to axis) and lower cervical injuries (C3–C7). The mechanism of injury to the cervical column can be divided into four major groups: hyperflexion, hyperextension, rotation, and vertical compression with frequent variations that include components of the major groups (e.g., flexion and rotation). Hyperflexion injuries include anterior subluxation, bilateral interfacetal dislocation, simple wedge fracture, fracture of the spinous process, teardrop fracture, and odontoid (dens) fracture. Of these the simple wedge fractures and isolated spinous process fractures are considered initially stable, while the other fractures are considered unstable such as the bilateral interfacetal dislocation and the teardrop fracture. The odontoid fracture can be considered stable or unstable depending on the type of fracture type.

Hyperextension injuries are less frequent than the hyperflexion injuries and result in the following types of fractures and injuries: dislocation, avulsion fracture, or fracture of the posterior arch of C1, teardrop fracture of C2, laminar fracture, and traumatic spondylolisthesis of C2 (Hangman's fracture). Most of these injuries with the exception of Hangman's fracture are defined as stable fractures; however, this does not imply that these injuries should go untreated. The hyperextension injuries are often associated with central cord syndrome especially in patients with preexisting cervical spondylosis and usually produce diffuse prevertebral soft tissue swelling. Vertical compression results in the Jefferson fracture which involves atlas and is considered unstable or burst fractures. A common site for injuries is the craniocervical junction (CCJ) and the atlantoaxial joint, which is the most mobile portion of the spine as it predominantly relies on the ligamentous framework for stability. The imaging findings of important CCJ injuries, such as atlantooccipital dissociation, occipital condyle fractures, atlas fractures with transverse ligament rupture, atlantoaxial distraction, and traumatic rotatory subluxation, are important to recognize in the acute setting as for the patient management

Fractures in the lower thoracic and lumbar spine differ from those in the cervical spine. The thoracic and lumbar fractures are often complex and due to a combination of mechanisms. The thoracic cage confers substantial biomechanical protection to the thoracic spine. Therefore, statistically, most injuries occur where the thoracic cage ends, the thoracolumbar junction. When injuries occur in the upper or middle thoracic spine, it is usually a result of major trauma, e.g., high-velocity trauma such as motor vehicular accidents. The most common fracture, at the thoracolumbar junction, is the simple compression or wedge fracture (50 % of all fractures) which is considered stable. The remaining types of fractures among those the so-called seat belt injury, which can be divided into three subtypes, type I (Chance fracture) that involves the posterior bony elements, type II (Smith fracture) that involves the posterior ligaments, and type III where the annulus fibrosus is ruptured allowing for subluxation, are considered unstable fractures [22]. The most common of all thoracolumbar fracture – the burst fractures – accounts for 64–81 % of all thoracolumbar fractures. The burst fracture, which can be divided into five subtypes, is associated with high incidence of injuries to the spinal cord, conus medullaris, cauda equina, and nerve roots [23]. It is important to remember that a burst fracture involving anterior and middle column can be misdiagnosed as mere compression fracture on plain films and, therefore, may be misinterpreted as a simple compression or mild wedge fracture that involves only anterior column. CT has improved characterization of these injuries.

Traumatic Disc Herniation and Ligamentous Injury

Traumatic disc injuries are caused by distraction and shearing in sudden hyperflexion or extension. A direct injury to the disc is more common than post-traumatic disc extrusion. Traumatic disc herniation should be considered when the disc exhibits high signal on T2-weighted images especially when traumatic vertebral body fractures and/or ligamentous injury is present at the same level [13]. Extruded disc material may extend into the epidural or prevertebral space. When there is a gap between parts of the vertebrae or by increased signal in the ligament or adjacent structures on T2W and STIR images, a ligamentous injury is suspected. Up to 25 % of all cervical injuries will demonstrate signal changes in the posterior ligamentous complex. This finding does not equate with instability. Ligamentous injury without underlying fracture in the cervical spine is rare [24]. Disruption of the anterior longitudinal ligament is associated with hyperextension mechanisms with associated injury to the prevertebral muscles and intervertebral discs and can be identified as interruption of the normal linear band of hypointense signal of the ligament on T1W images. Hyperflexion and distraction forces may cause disruption of the posterior ligament complex which is manifested by increased distance between spinous processes on lateral radiography and increased signal in the interspinous region on MRI sagittal STIR sequences. Abnormal angulation, distraction, and subluxation are often recognized on initial CT study.

Injuries to the Spinal Cord

A majority of patients with spinal cord injury (80 %) harbor multisystem injuries [25]; typically associated injuries include other bone fractures (29.3 %) and brain injury (11.5 %) [26]. Nearly all spinal cord injuries damage both upper and lower motor neurons because they involve both the gray matter and descending white matter tracts at the level of injury. The American Spinal Injury Association (ASIA) has suggested a comprehensive set of standardized clinical measurements which are based upon a detailed sensory and motor examination of all dermatomes and myotomes. The neurological deficit that results from injury to the spinal cord depends primarily upon the extent of damage at the injury site and the cranial-caudal location of the damage (i.e., the neurological level of injury or NLI); anatomically higher injuries produce a greater neurological deficit (e.g., cervical injury=quadriparesis, thoracic injury=paraparesis). These comprehensive set of standardized clinical measurements have been adopted worldwide. While functional transection of the spinal cord is relatively frequent in spinal cord injury, true mechanical transection is relatively rare and is confined to penetrating type injuries or extensive fracture-dislocations/translocations. The neurological deficits associated with spinal cord injuries are further categorized into anterior cord syndrome, Brown-Sequard syndrome, central cord syndrome, conus medullaris syndrome, and cauda equina syndrome. Spontaneous neurological recovery after spinal cord injury overall is relatively poor and largely depends upon the degree of neurological deficit identified at the time of injury. Of the different cord syndromes, the anterior cord syndrome has the worst prognosis of all cord syndromes, especially, if no recovery is noticed during the first 72 h after injury.

Spinal Cord Hemorrhage

Post-traumatic spinal cord hemorrhage or hemorrhagic contusion is defined as the presence of a discrete area of hemorrhage within the spinal cord after an injury. The most common location for hemorrhage to accumulate is within the central gray matter of the spinal cord and centered at the point of mechanical impact [14, 27, 28]. Experimental and autopsy pathologic studies have shown that the underlying lesion most often will be hemorrhagic necrosis of the spinal cord while true hematomyelia will rarely be found [29]. There are significant clinical implications if there is identification of frank hemorrhage in the cervical spinal cord following trauma on an MRI examination. Originally it was thought that detection of intramedullary hemorrhage was predictive of a complete injury. However, the increased sensitivity and spatial resolution of current MRI techniques has shown that even small amounts of hemorrhage are identifiable in incomplete lesions. Therefore, the basic construct has been altered such that the detection of a sizable focus of blood (>4 mm in length on sagittal images) in the cervical spinal cord is often indicative of a complete neurological injury [30]. The anatomic location of the hemorrhage closely corresponds to the neurological level of injury, and the presence of frank hemorrhage implies a poor potential for neurological recovery (Fig. 2) [14, 27, 28, 31–33].

Spinal Cord Edema

Spinal cord edema is defined as a focus of abnormal high signal intensity seen on MRI T2-weighted images [28]. Presumably, this signal abnormality reflects a focal accumulation of intracellular and interstitial fluid in response to injury [14, 28, 34, 35]. Edema is usually well defined on the mid-sagittal T2-weighted image, while the axial T2-weighted images offer additional information in regard to involvement of structures in cross section (Fig. 2). Spinal cord edema involves a variable length of spinal cord above and below the level of injury, with discrete boundaries adjacent to uninvolved parenchyma, and is invariably associated with some degree of spinal cord swelling. The length of spinal cord affected by edema is directly proportional to the degree of initial neurological deficit [27, 36]. Notable is that spinal cord edema can occur without MRI evidence of intramedullary hemorrhage. Cord edema alone connotes a more favorable prognosis than cord hemorrhage.

Fig. 2 Acute hemorrhagic spinal cord injury. There is a flexion type injury of C5 with acute ventral angulation. The spinal cord is markedly swollen with edema spanning the entire length of the spinal cord. There is a central hemorrhagic focus which is of low signal intensity that spans from C4 to C6. Note the disruption of the posterior spinal soft tissues

Injuries to the Pediatric Spine and Spinal Cord

Spinal injuries are generally less common in the pediatric population compared to adults with cervical spine injuries being most frequent spine injury of all spine injuries occurring in up to 40–60 % of all injuries in children. The etiology varies depending on the age of the child. The most common cause of pediatric cervical spine injury is a motor vehicle accident, but also obstetric complication, fall, and child abuse are known causes. In the adolescent sports and diving accidents are other well-known causes. The specific biomechanics of the pediatric cervical spine leads to a different distribution of injuries and distinct radiological features and represents a distinct clinical entity compared to those seen in adults. Young children have a propensity for injuries to the CCJ, upper cervical injuries (i.e., cranial base to C2), whereas older children are prone to lower cervical injuries similar to those seen in adults. The spinal cervical injuries in children less than 8 years of age demonstrate a high incidence of subluxation without fractures. The biomechanical differences are explained by the relative ratio of the size of the cranium to the body in the young child, lack of ligamentous stability, poor muscle strength, and increased forces relative to the older child and adult. Children are also more prone to spinal cord injury with otherwise normal radiographs, the so-called SCIWORA (spinal cord injury without radiographic abnormality), compared to adults. This is especially evident in children younger than 9 years of age where there is a high incidence of reported complete cord injuries associated with SCIWORA. Suggested mechanisms of the SCIWORA include hyperextension or flexion injuries to the immature and the inherently elastic spine, which is vulnerable to external forces and allows for significant intersegmental movement and transient soft disc protrusion, resulting in distraction injuries, and/or ischemic injury of the spinal cord [37]. The elasticity of the spine allows it to stretch up to 5 cm before rupture, whereas the spinal cord, which is anchored to the brachial plexus superiorly and the cauda equina inferiorly, ruptures after 4–6 mm of traction [38]. As MRI is readily capable of detecting the soft tissue injury component, the concept of SCIWORA is less relevant.

The imaging algorithm for pediatric spinal trauma is somewhat different than that for adults. MDCT is used more judiciously due to radiation exposure considerations, and at many places lower-dose radiography is often utilized initially. MRI is always used if there is a consideration of a pure soft tissue injury or neurological deficit.

Neurological Recovery After Spinal Cord Injury

Although there are no pharmacologic “cures” for spinal cord injury, spontaneous neurological recovery after injury can occur, and it largely depends upon the severity of the initial neurological deficit, the neurological level of injury, patient age, and comorbidities. Very few patients with a neurologically complete injury (i.e., no motor or sensory function below the injury level) actually regain any useful function below the injury level although most patients will spontaneously improve by one neurological level (e.g., a C5 level spontaneously descends to a C6 level). Even these small improvements can have a substantial impact on a patients’ capacity to function independently.

The role of MRI to predict capacity for spontaneous neurological recovery after cervical SCI has been evaluated. Although there is considerable overlap in results, some general characterizations about the MRI appearance of SCI and neurological recovery are evident. Intramedullary hemorrhage four millimeters or greater is equated with a severe neurological deficit and a poor prognosis. Cord edema alone is indicative of a mild to moderate initial neurological deficit and a better capacity for spontaneous neurological improvement. The length of the cord lesion may also correlate with the initial deficit and in the neurological outcome. As novel pharmacologic therapies for SCI are developed and tested, MRI will likely play a more essential role in characterizing the injury and helping to select patients for clinical trials.

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