Pediatric Spinal Trauma

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Abstract

Pediatric spinal trauma is unique because of various reasons (Tortori-Donati et al. 2005; Hollingshead and Castillo 2011). First of all, the biomechanical properties of the initially predominantly cartilaginous pediatric spine are very different compared to the adult spine. In the early years of life, the stability of the pediatric spine relies predominantly on the cartilaginous spine and the relatively lax ligaments. The pediatric spine is consequently more mobile and deformable compared to adults. Traumatic forces will be absorbed differently in children and variably for the various age groups. Vertebral fractures are less frequent in young children compared to adults. Dislocations, ligamentous injuries, epiphyseal detachments, and lesions of the ossification centers are more frequent. With progressing age and physical activity of the child, the paraspinal musculature will develop and contribute to the dynamic stability of the spinal column. In addition, the proportions of the pediatric body change dramatically in the first years of life. Young children have a relatively large and heavy head compared with the torso. Later in life, the head-to-torso ratio progressively decreases. This is of particular importance for the craniocervical junction. Next to the large head and the “weak” neck musculature, the “young” pediatric spine is also more mobile due to the shallow occipital condyles, horizontal orientation of the facet joints (30° vs. 60–70° in adults), small uncinate processes, immature uncovertebral joints, increased elasticity of the posterior joint capsules, and cartilaginous junction between the vertebral bodies and their end plates (VanderHave et al. 2011). The transverse (extension/flexion) and rotational mobility of the cervical spine is increased compared to adults. This makes the craniocervical junction and upper cervical spine very vulnerable for sudden acceleration and deceleration forces and trauma-related injuries. Most pediatric spinal traumas occur consequently in the cervical spine (80%). In children younger than 8 years, primarily the first three cervical segments are involved. With progressive age, the fulcrum of flexion gradually shifts caudally from C2/3 to C5/6. In older children and young adults, the lower cervical spine is consequently more frequently affected. At about 10 years of age, the more typical adult distribution of injury is noted, affecting predominantly the cervicothoracic junction. Similar to adult patients, in children, the thoracic spine is less frequently affected due to the stabilizing effects of the adjacent rib cage. The lumbar spine is again more mobile.

Introduction

Pediatric spinal trauma is unique because of various reasons (Tortori-Donati et al. 2005; Hollingshead and Castillo 2011). First of all, the biomechanical properties of the initially predominantly cartilaginous pediatric spine are very different compared to the adult spine. In the early years of life, the stability of the pediatric spine relies predominantly on the cartilaginous spine and the relatively lax ligaments. The pediatric spine is consequently more mobile and deformable compared to adults. Traumatic forces will be absorbed differently in children and variably for the various age groups. Vertebral fractures are less

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frequent in young children compared to adults. Dislocations, ligamentous injuries, epiphyseal detachments, and lesions of the ossification centers are more frequent. With progressing age and physical activity of the child, the paraspinal musculature will develop and contribute to the dynamic stability of the spinal column. In addition, the proportions of the pediatric body change dramatically in the first years of life. Young children have a relatively large and heavy head compared with the torso. Later in life, the head-to-torso ratio progressively decreases. This is of particular importance for the craniocervical junction. Next to the large head and the “weak” neck musculature, the “young” pediatric spine is also more mobile due to the shallow occipital condyles, horizontal orientation of the facet joints (30° vs. 60–70° in adults), small uncinate processes, immature uncovertebral joints, increased elasticity of the posterior joint capsules, and cartilaginous junction between the vertebral bodies and their end plates (VanderHave et al. 2011). The transverse (extension/flexion) and rotational mobility of the cervical spine is increased compared to adults. This makes the craniocervical junction and upper cervical spine very vulnerable for sudden acceleration and deceleration forces and trauma-related injuries. Most pediatric spinal traumas occur consequently in the cervical spine (80 %). In children younger than 8 years, primarily the first three cervical segments are involved. With progressive age, the fulcrum of flexion gradually shifts caudally from C2/3 to C5/6. In older children and young adults, the lower cervical spine is consequently more frequently affected. At about 10 years of age, the more typical adult distribution of injury is noted, affecting predominantly the cervicothoracic junction. Similar to adult patients, in children, the thoracic spine is less frequently affected due to the stabilizing effects of the adjacent rib cage. The lumbar spine is again more mobile.

Another feature that increases the risks of spinal trauma in children is that young children typically have less well-developed protective reflexes if exposed to an approaching force. Translational forces at the craniocervical junction may result in devastating, frequently lifelong lasting injuries to the lower brainstem and upper cervical spinal cord. Young children with traumatic brain injury (TBI) should be evaluated for concomitant injuries to the craniocervical junction. Next to the immediate injury to the spinal cord, injuries to the developing cartilaginous vertebral column and disco-ligamentary apparatus may also interfere with the ongoing development of the spinal column. Epiphyseal ring detachments, injuries to the ossification centers, or dislocations may result in spinal maldevelopment and long-lasting spinal instability including scoliosis.

Finally, it is important to be aware that depending on their age and physical activity, infants and children are exposed to different kinds of traumas. In neonates, the spine and spinal cord may be injured secondary to a traumatic, forceful delivery; in young infants, shaken baby injuries and non-accidental injury may result in trauma of the craniocervical junction; in older children, direct blows to the spine may occur after falls or aggressive sport activities. Later in life, children predominantly suffer spinal injuries from high-speed motor vehicle accidents. Airbag-related injuries comprise a relatively new group of spinal injuries that depend on the size and position of the infant or child in relation to the rapidly inflating airbags in the case of a motor vehicle collision.

Knowledge about the kind of trauma, age-dependent vulnerability of the spinal column and cord, as well as risks of associated injuries outside of the central nervous system (CNS) is mandatory for correct diagnosis. Frequently, trauma to the spinal column and cord occurs as part of a more extensive accident including TBI. In addition, simultaneous trauma to the chest and abdomen with possible cardiopulmonary or parenchymatous complications may aggravate the injury of the spinal cord. Hypoxia-ischemia, spinal cord swelling, epidural hematomas, release of excitatory neurotransmitters, and various additional complex inflammatory processes to mention a few may result in significant secondary injuries.
Epidemiology

Most pediatric spinal injuries occur in conjunction with motor vehicle accidents (52 %), followed by sports-related injuries (27 %), falls (15 %), child abuse (3 %), and various other less frequent accidents (Jones et al. 2011). In the vast majority of motor vehicle accidents, spinal injury occurs because the child was unrestrained or incorrectly restrained in the car. Falls are more frequent in children 8 years and younger, while sport injuries occur more often in older children. The unique biomechanics of the pediatric developing and growing spine are responsible for different sports-related injuries. The rate and also often the severity of injuries increase with the child’s age and ability level. Injuries may occur while a child is skiing, cycling, diving, wrestling, performing gymnastics, or playing team sports like soccer, football, or ice hockey (Maxfield 2010). Unfortunately, spinal injury may also occur as a consequence of child abuse either by shaking a young baby with resultant injuries to predominantly the craniocervical junction or due to forces exerted directly to the spine while the child is being beaten. In addition, subdural and epidural blood may extend from the cranial vault into the spinal canal (Fig. 1).

Children with cervical spine injury are more likely to have additional neurological injury. The overall mortality rate of pediatric patients with cervical spine injuries ranges between 16 % and 18 % (Jones et al. 2011). The morbidity and mortality rate is especially high in children with an upper cervical spine injury or atlanto-occipital dislocation (Jones et al. 2011).

Imaging

The goal of any diagnostic imaging should be to collect as much relevant and specific information about the location, degree, and quality of primary injury in order to start immediate treatment and to limit or prevent secondary injury. Imaging should be fast, be readily available, and not interfere with the emergent treatment and should of course be highly sensitive and specific.

The tool box of available imaging modalities is diverse and includes static and dynamic conventional radiography (CXR), computed tomography (CT), and magnetic resonance imaging (MRI). Depending on the patient’s acute physical status and the available equipment, different diagnostic approaches may be chosen. CXR of the spine is still being used as a first line of imaging. However, in many institutions, children who suffered from serious traumas typically first receive a CT study of the region of suspected injury. In particular, children who suffered from an unwitnessed traumatic brain and/or spine injury, unconscious children, rapidly deteriorating children, and children with focal neurological deficit should receive primarily a head and spine CT. Multiplanar reconstructions of the spine show fractures and dislocations with high sensitivity and specificity. Next to bone algorithm reconstructions, soft tissue images are necessary to depict focal spinal cord injuries, epidural hematomas, and adjacent soft tissue and ligamentous injuries (Fig. 2). In addition, vascular injuries may occasionally be noted. Finally, if additional injuries to the chest and abdomen are present or suspected, whole-body CT imaging may be performed. MRI is typically performed after a CT study if a spinal cord lesion is suspected (focal neurological deficits) or if the CXR or CT imaging findings do not explain the clinical/neurological symptoms adequately. In addition, MRI is frequently used as a follow-up imaging tool in order to reduce the radiation dose. Even in children who have stabilizing hardware in place, MRI may be considered. The hardware that is nowadays being used is usually non-ferromagnetic and will typically only induce a focal signal loss in the immediate region of the hardware. The segments above and below the surgical site are usually free of significant artifacts. In addition, new developments and sequences have significantly reduced the degree of susceptibility artifacts. MRI typically includes multiplanar T1- and T2-weighted imaging as well as either short tau inversion recovery (STIR) or fat-saturated T2-weighted sequences.
Intravenous contrast injection is usually not necessary. High-resolution heavily T2-weighted sequences, like the three-dimensional constructive interference in steady-state (CISS) sequence, can be helpful to study the anatomy of the spinal cord and nerve roots as well as the spinous ligaments in exquisite anatomical detail. This sequence is however not sensitive for subtle intramedullary signal alterations, e.g., edema due to contusion or infarction.

Fig. 1 Axial FLAIR of the brain and axial T2, sagittal T1, and T2-weighted MRI of a neonate who suffered from non-accidental injury. A small FLAIR hyperintense subdural hematoma is noted along the right parietal hemisphere, partially extending into the interhemispheric fissure. In addition a coexisting moderate-sized intradural, subarachnoid T1-hyperintense, T2-hypointense hematoma is noted within the dorsal, dependent lower part of the dural sac (arrows).

Fig. 2 Sagittal CT (soft tissue algorithm) and sagittal T2-weighted MR images of two children who have suffered a craniocervical junction injury. On CT, a moderately dense retroclival hematoma (arrow) is noted which displaces the adjacent lower brainstem. The apical ligaments between the dens/anterior arch of C1 and the clivus are intact and outlined by hypodense fat. No osseous lesion was noted. In the second child, the exquisite soft tissue resolution of MRI shows a disrupted (arrowhead) and displaced T2-hypointense tectorial membrane that, in combination with a retroclival hematoma, displaces the lower brainstem. In addition, the apical ligament at the tip of the dens is also ruptured.

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Ultrasound has only a very limited role in the diagnostic workup of traumatic spine injuries. In the neonates, the spinal canal can be evaluated in between the ossification centers of the vertebral bodies; however, spinal US is predominantly used for the evaluation of spinal malformations rather than for posttraumatic lesions.

Bone scintigraphy may be considered if a complicating osteomyelitis is suspected or in the case where hardware prevents a diagnostic MRI study of the region of interest.

Conventional radiography remains important in children suspected of non-accidental injury (skeletal survey). Depending on the age of the child, various “typical” posttraumatic lesions can be seen. Child abuse should be suspected if the imaging findings cannot adequately be explained by the reported trauma mechanism and/or if “peculiar” fractures are noted, including isolated spinous process fractures which are more suggestive of non-accidental injury than of accidental trauma.

The Normal Developing Pediatric Spinal Column may Mimic Pediatric Spinal Injuries

The developing pediatric spinal skeleton may be challenging. The cartilaginous nature of the young skeleton, the presence of multiple ossification centers and complex synchondroses (Figs. 3 and 4), as well as a high variability in the normal development may result in misdiagnosis. Synchondroses, not yet ossified parts of the skeleton, or residual cartilaginous components may be misinterpreted as fractures (Jones et al. 2011; Maxfield 2010; Lustrin et al. 2003). The different shape of the young pediatric vertebral bodies with a physiological anterior wedging may be interpreted as a compression fracture (Fig. 5). In addition, the hypermobility of the spine with physiological subluxation of especially C2 relative to C3 may mimic traumatic injury/dislocation (Fig. 5). Finally, various metabolic disorders (e.g., mucopolysaccharidoses) and skeletal dysplasias (e.g., achondroplasia) or segmentation/formation anomalies of the vertebral column may result in a deformity of the osseous elements suggesting traumatic injuries (Fig. 6) (Mcmaster and Singh 1999). Also, various connective tissue disorders as well as chromosomal anomalies (e.g., trisomy 21) may result in an increased mobility of the spinal column.
Frequently, widening of the prevertebral space, especially along the cervical spine, is used as an indirect sign for an adjacent spinal injury. However, depending on the degree of inspiration, the width of the prevertebral space may show a significant physiological variability in young children. Moreover, the adenoids and cervical lymphatics (e.g., pharyngeal lymphoid ring of Waldeyer) are more prominent in children compared to adults.

Finally, it should not be forgotten that traumatic injuries and fractures may be missed on CXR and CT because the injured components may not yet be ossified and consequently remain undetected on "bone

Fig. 4 AP conventional radiography of the thoracic spine of an infant and coronal 3D CT and axial CT image of two healthy neonates show the physiological synchondroses of the vertebral bodies which should not be mistaken for posttraumatic lesions. Familiarity with the normal progressing development of the vertebral bodies is essential

Fig. 5 Lateral conventional radiography of a healthy infant shows the typical wedge-shaped configuration of the developing vertebral bodies as well as the physiological subluxation between C2 and C3, which should be less than 3 mm. In addition, the atlantodental interval is wider compared to adults (up to 4.5 mm in children, compared to 3 mm in adults). The spinolaminar line, or Swischuk’s line (dotted line), may be helpful to confirm the normal alignment of the vertebral bodies.

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Finally, it should not be forgotten that traumatic injuries and fractures may be missed on CXR and CT because the injured components may not yet be ossified and consequently remain undetected on “bone
Each radiologist and physician who is interpreting pediatric spine studies must be familiar with the normal, developing pediatric skeleton to prevent misdiagnosis.

**Pediatric Spinal Injuries**

**Craniocervical Junction and Cervical Spine**
A spectrum of posttraumatic lesions may be encountered at the craniocervical junction. Depending on the trauma mechanism, translational, flexion/extension, distraction, and compression injuries or fractures may be noted. Most of the lesions are noted at the immediate craniocervical junction. In the mildest forms, the ligaments are stretched or torn with or without dislocation. In more severe cases, epiphyseal detachment or fractures may be seen (Figs. 7 and 8). Most importantly, compression, contusion, or transection of the adjacent brainstem and spinal cord may occur. Neurological deficit is typically acute and has a poor prognosis. In addition, coexistent intracranial lesions may be present and should be ruled out if there is a suggestive neurological presentation or trauma mechanism. In high-speed motor vehicle accidents with acute acceleration-deceleration forces, diffuse axonal injury may be coexistent with ligamentous injuries at the craniocervical junction (Fig. 9).

**Ligamentous Injury**
In mild forms, the alignment is preserved, but the ligaments are stretched or torn. CXR and CT may be unremarkable with exception of a straightening of the physiological cervical lordosis (guarding) and a mild paravertebral edema or an epidural retroclival or intraspinal hematoma. T2-weighted MRI may show an increased T2 signal of the injured ligaments, occasionally with T2-hyperintense edema of the injured ligaments. The high-resolution T2-weighted CISS sequence may directly show the interruption/disruption of the injured ligaments. This MR sequence is especially helpful for the alar and apical ligaments as well as the tectorial membrane. Retroclival hematomas may displace the tectorial membrane and extend into the epidural space of the upper spinal canal (Figs. 2 and 9) (Meoded et al. 2011). T2-hyperintense
edema may be seen along the epiphyseal plates as well as along the insertion of the ligaments within the subchondral bone. Adjacent soft tissue edema or hematomas may be seen. Vascular injuries like dissections should be ruled out.

Fig. 7 Sagittal T2-weighted MR images of an infant who sustained a craniocervical acceleration-deceleration injury. The traction forces injured predominantly the cartilaginous and ligamentous components of the craniocervical junction with separation of the T2-hypointense ossification center of the tip of the dens from its base. T2-hyperintense fluid is noted between the separated fragments as well as between the widened joints between C1 and C2 (arrows). In addition, the dorsal longitudinal ligament is partially torn. Finally, a focal T2-hyperintense focal contusion is noted within the upper cervical spinal cord (thick arrow). Conventional radiography and likely also CT are at risk to underestimate the full extent and degree of injury.

Fig. 8 Sagittal T1, T2, and T2* and follow-up T2-weighted MR images of a child who was a victim of a high-speed motor vehicle accident. An ill-defined T1- and T2-hyperintense injury occurred to the lower brainstem and upper cervical spinal cord. Minimal T1-hyperintense blood clots are noted anterior to the spinal cord at level of C4/C5. In addition, a large T1-hypointense, T2-hyperintense fluid collection is noted in the prevertebral space which appears to communicate with the intradural cerebrospinal fluid (CSF) space surrounding the spinal cord. A T2-hypointense flow-related signal void is noted connecting both compartments (arrow). Finally, the inferior end plate of C6 appears disrupted from C6 and is lining the intact intervertebral disk C6/C7 which is attached to C7. This injury implies that the anterior and posterior longitudinal ligaments are torn and that a kind of Salter Harris type I fracture occurred. Follow-up imaging reveals a high-grade atrophy of the cervical spinal cord, secondary deformity of the cervical spinal alignment, and a complete resolution of the prevertebral fluid collection.

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Due to the high mobility and flexibility of the pediatric spine, an intermittent subluxation/luxation may have occurred during the time of trauma, which has spontaneously recovered on follow-up. The CXR and CT findings are consequently underestimating the degree of soft tissue and ligamentous injury. MRI is, however, highly sensitive to show the resulting injuries that may affect the ligaments and possibly also the spinal cord and brainstem. This category of injury is also overlapping with an entity known as SCIWORA (spinal cord injury without radiographic abnormality) (Fig. 10). Pang and Wilberger defined this entity as marked by objective signs of spinal cord injury, without evidence of ligamentous injury or fractures on plain films or tomographic studies (Pang and Wilberger 1982). SCIWORA has typically been described to affect children and is believed to involve the cervical spine most frequently. Flexion and extension but also lateral bending, distraction, rotation, axial loading, or combinations of these forces are the most common mechanism of injury. Again, MRI usually shows the trauma-related injuries that remained undetected on CXR or CT in better detail. Hematomyelia (i.e., spinal cord hemorrhage) may also rarely occur in patients with distraction injury to the craniocervical junction (Fig. 11).

### Atlanto-Occipital and Atlanto-Axial Dislocation

In the more severe forms, an axial dislocation of C1 in relation to the occiput (atlanto-occipital dislocation) may be encountered or between C1 and C2 (atlanto-axial dislocation) (Figs. 12, 13, and 14). The spinal canal is typically narrowed with compression and injury to the spinal cord. Anterior
Fig. 10  Sagittal T2-weighted and STIR MR images of a young adolescent who suffered from a unwitnessed, apparently minor head and neck trauma and who complained about tingling sensations in his upper extremities. Conventional radiography and CT imaging was unremarkable. MRI shows a focal T2-hyperintense lesion within the cervical spinal cord (arrows) representing a small area of contusion/injury. This presentation is compatible with the diagnosis of SCIWORA. Follow-up imaging showed a discrete area of gliosis with near-complete recovery of the symptoms.

Fig. 11  Hematomyelia in a 1.5-year-old girl with recent distraction injury to the neck. Sagittal T1, T2, and T2*-weighted images show focal acute intramedullary hemorrhage. Axial T2-weighted image and axial CT scan confirm intramedullary bleeding with surrounding edema. Case courtesy of Andrea Rossi, Genoa, Italy
Dislocations are more frequently seen than posterior dislocations. The facet joints as well as the occipital condyles should be carefully evaluated for additional injuries and dislocations (Figs. 15, 16, and 17).

**Atlanto-Axial Dissociation**

In the most severe forms, a significant axial/vertical atlanto-occipital dislocation, better known as dissociation, may be encountered (Fig. 18). These injuries typically occur in high-speed motor vehicle accidents and are characterized by a complete rupture of the ligaments between the occiput and C1/C2 with subsequent “separation” of the spinal column from the skull. The spinal cord is usually severely injured with poor prognosis. These injuries may also be seen in young children who were struck by a rapidly deploying airbag while seated in a forward facing car seat. Large pre- and paravertebral hematomas occur.

**Cervical Fractures**

The spectrum of cervical fractures in children is similar to the “adult” fractures; however, the incidence, distribution, and location differ (Figs. 16, 17, and 19). Atlas fractures, like the Jefferson fracture, are typically seen as a result of an axial compression after a fall onto the head (diving accidents), while anterior and posterior arch fractures of the atlas typically result from a focal C1/C2 hyperextension.
Fractures of the axis include the Anderson fracture, which typically occurs as a complication of traumatic hyperflexion, and the Hangman fracture, which in turn is seen after traumatic hyperextension. Compression fractures (C3-C7) typically result from traumatic hyperflexion and present with an increased anterior wedging of the cervical vertebral bodies. CXR and especially multiplanar coronal and sagittal CT reconstructions usually easily identify the kind and degree of injury/fracture. MRI may help to characterize and date the fracture. Occasionally, it is difficult to differentiate between an anterior wedging of the vertebral bodies as a normal developmental variant and that secondary to a preexistent systemic disorder and a posttraumatic anterior reduction in height. T2-hyperintense bone marrow edema as well as paravertebral soft tissue edema will suggest acute injury.

With progressing age, the middle and lower cervical spine will be more frequently affected. The region of maximal mobility migrates from the C2/C3 region toward the adult region at the level of C5/C7/T1. Consequently, more frequently, posttraumatic lesions resulting from hyperextension/hyperflexion will be seen in the middle and lower cervical spine at older age.
Thoracic and Lumbar Spine

Fractures

With progressing static and dynamic stability, the predominant location of spinal injuries migrates toward the thoracic and lumbar spine (children >10 years). Fractures are typically seen at the thoracolumbar junction and in the region of the lumbar spine (Bollmann et al. 2011). Fractures occur less frequently in the

Fig. 14  Sagittal T2- and T1-weighted initial and follow-up MR images of the same child as shown in Fig. 12. On MRI, the full extent of soft tissue injury is seen in much better detail. A focal contusion of the lower brainstem and upper cervical spinal cord is identified, as well as a significant ligamentous injury of the craniocervical junction. On follow-up imaging, significant spinal cord atrophy is noted. In addition, a significant deformity is noted of the lower cervical vertebral bodies which did not appear injured on the initial imaging. This deformity of non-injured vertebral elements is typically seen in young children and is believed to be secondary to the fact that an early trauma may result in a secondary, aberrant development of the spinal column

Fig. 15  Sagittal, coronal, and axial CT images of a child with posttraumatic torticollis and neck pain due to a fracture of the left occipital condyle. The ossified tip of the dens is mildly dislocated in relation to the atlas which is best seen on the axial images. No additional fractures were noted; MRI showed a small epidural hemorrhage at the foramen of magnum without evidence of spinal cord injury

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thoracic spine because of the stabilizing effects of the rib cage. Thoracic and lumbar fractures include lateral shear-translation fractures, compression fractures (typically from falls), burst fractures, Chance

Fig. 16 Coronal, sagittal, and axial images of a child with an odontoid fracture and C0/C1 dislocation. The tip of the dens is fractured at the level of the previous synchondrosis between tip and base of the dens. The foramen of magnum is secondarily narrowed due to the anterior dislocation of the atlas

Fig. 17 Coronal, axial 2D, coronal 3D CT, and sagittal, axial T2-weighted MR images of a child with a left lateral odontoid tip fracture and an associated rotational subluxation of C1 in relation to C2. MRI excluded a spinal cord injury or spinal canal stenosis. Mild amount of T2-hyperintense fluid is seen between the anterior dens and adjacent anterior arch of the atlas. 3D CT is very helpful to evaluate the degree of subluxation

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fracture (flexion-distraction injury), and focal, direct impact fractures. Various additional fractures involving the neural arch and posterior or lateral elements of the spine may be encountered as complication of direct impact.

Compression fractures are characterized by wedge-shaped deformity of the involved vertebral body with interruption/fracture of the anterior vertebral contour (Fig. 20). Compression fractures are typically stable if they involve only the anterior column. Burst fractures occur as the complication of an axial force, resulting in a fracture of both the anterior and posterior contour of the involved vertebral body. Bony fragments may be dislocated into the spinal canal, compressing the adjacent neuronal structures (Figs. 21 and 22). Additional dislocations may be seen in more severe injuries. These fractures result from various combinations of flexion and axial compression. Lateral forces may also result in compression or burst

Fig. 18 Lateral CT localizer, soft tissue, and bone algorithm sagittal and coronal CT images of the cervical spine of an adolescent boy who sustained severe craniocervical junction dissociation after a high-speed motor vehicle accident. He was ejected from the car and resuscitated at the scene. A significant vertical and anterior dissociation of the craniocervical junction is noted. High-grade narrowing of the spinal canal as well as a large prevertebral and moderate-sized anterior epidural hematoma is seen. Subarachnoid blood is seen outlining the brainstem. The child subsequently died
fractures; however, in these traumas, additional lateral dislocations can be noted (Figs. 23, 24, 25, and 26). Diffusion-weighted and diffusion tensor imaging of the spinal cord may be helpful to evaluate the degree of spinal cord injury and integrity of fiber tracts (Fig. 26).

**Chance Fractures**

The Chance fractures, named after the British radiologist G. C. Chance who first described in 1948 this group of fractures for the lumbar region, are characterized by a transverse or oblique fracture that involves all three longitudinal vertebral columns (Figs. 27 and 28) (Chance 1948; Davis et al. 2004). This fracture results from a combined flexion-distraction mechanism around a fulcrum, most commonly a seat belt. The Chance fracture is consequently also known as seat belt or lap belt fracture. The anterior vertebral body is typically compressed, while the posterior vertebral body height is increased by the distraction component of the injury. The posterior extension of the distracting forces distracts the posterior elements with increased interspinous distance and widened facet joints. Concomitant ligamentous injury, e.g., rupture
of the posterior longitudinal and interspinous ligaments, occurs in variable degrees and determines stability. Anterolisthesis at the fracture level may result in significant compression of the spinal cord or cauda equina. Most injuries of the lower back are at the thoracolumbar junction because of its relative high mobility. Children with seat belt injuries frequently have additional internal injuries because of a somewhat less stable rib cage and pelvis compared to adults. Imaging should consequently also include evaluation of the thoracic and abdominal organs and vasculature (Figs. 28 and 29).
Conventional lateral radiography and sagittal and coronal CT images show L1 compression/burst fracture with retropulsion of the fracture fragments into the spinal canal as in the child shown in Fig. 20. An additional superior end plate fracture affecting T11 is noted. This case illustrates that the individual vertebral segments may be skipped after trauma.

Coronal 2D and 3D CT images of a 17-year-old male who fell 12 f of a roof. In addition to multilevel compression fractures, significant lateral dislocation is noted with partial overriding of the vertebral bodies. Despite the significant dislocation, no serious neurological deficits were noted on clinical examination.
Fig. 24  Sagittal STIR, T1-weighted and curved reformatted T2-weighted MR images (same case as Fig. 22) confirm the multilevel compression fractures with significant T2-hyperintense bone marrow edema. The spinal canal is mildly narrowed; the spinal cord appears intact without significant edema.

Fig. 25  AP conventional radiography and coronal and sagittal CT images of a child with a lateral/superiorly dislocated L1 fracture similar to the patient in Figs. 22 and 23. This child also had very minimal neurological deficits despite the significant malalignment.
**Fig. 26** Matching sagittal and coronal T2- and diffusion-weighted MR images (same case as Fig. 24) show a similar significant dislocated L1 fracture with lateral and anterior dislocation of the distal spine. The diffusion-weighted imaging is unremarkable without focal spinal cord lesions supporting the minimal clinical symptoms.

**Fig. 27** Axial and sagittal CT images of a child with a classical Chance fracture with a compression fracture of the anterior L3 vertebral body and distraction of the posterior elements, resulting in an increased posterior interspinous distance (*double arrow*) and widened facet joints (*arrow*). Axial abdominal contrast-enhanced CT shows a bowel wall hematoma and free fluid/blood within the peritoneal cavity/small pelvis related to the seat belt injury.
**Fig. 28** Coronal soft window and coronal and sagittal bone window algorithm CT images show classical Chance fracture affecting T8 (arrow). Moderate amount of blood/free fluid is noted within the abdomen. Axial contrast-enhanced CT in soft tissue and lung window settings show a laceration of the anterior stomach (arrow) with air escaping into the peritoneal cavity (free air) partially outlining the falciform ligament. The stomach was injured due to the seat belt mechanism of injury.

**Fig. 29** Axial contrast-enhanced CT of a child with posttraumatic pancreatic fracture. The fractured area is hypoenhancing (arrow). In addition, contusion/laceration of the adjacent spleen is noted.
Non-accidental Injury
The spinal column may also be involved in non-accidental injury or child abuse. Depending on the used force and mechanism of trauma, nearly any kind of spinal injury may result. There are no pathognomonic injury patterns to confirm the non-accidental nature of the trauma. Some lesions may suggest non-accidental injury, such as isolated fractures of the spinous processes (resulting from direct blows to the back of the child), especially when the caregivers provide no adequate or matching trauma history. A complete diagnostic workup with skeletal survey, physical examination, and psychosocial evaluation should be performed.

Birth-Related Injury
Traumatic vaginal delivery may result in injuries of the craniocervical junction and cervicothoracic junction. Next to ligamentous and cartilaginous-osseous lesions, the spinal cord may be injured ranging from smaller focal hemorrhages up to complete transsections. In addition, nerve root avulsions and brachial plexus injuries may be seen.

Additional Risk Factors
Preexisting spinal pathologies, including spinal anomalies with defective or incomplete development of the neural elements, segmentation or formation anomalies of the osseous spine, spondylolysis, as well as various systemic diseases like metabolic disorders, bony dysplasia, or infectious diseases including spondylitis and retropharyngeal abscesses, may enhance the risk for and severity of spinal injury. Finally, various chromosomal abnormalities like Down syndrome increase the risk for injuries due to the increased ligamentous laxity.

Conclusions
The pediatric spine is very different compared to the adult spine; incidence, epidemiology, distribution, and character of spinal injuries are unique for the age of the patient. Imaging should evaluate the ligamentous and osteocartilaginous elements of the spine as well as the spinal cord including nerve roots and paraspinal plexuses. CXR and CT predominantly study the osseous complications, and MRI the soft tissue injuries of spinal trauma.

References


