RadioGraphics

Pediatric Cervical Spine: Normal Anatomy, Variants, and Trauma[1]

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LEARNING OBJECTIVES FOR TEST 1

After reading this article and taking the test, the reader will be able to:

- Describe the normal anatomy and variants of the pediatric cervical spine.
- Discuss the clinically important anatomic and biomechanical differences between the pediatric and adult cervical spines.
- Recognize different radiologic manifestations of pediatric cervical spine trauma.

Emergency radiologic evaluation of the pediatric cervical spine can be challenging because of the confusing appearance of synchondroses, normal anatomic variants, and injuries that are unique to children. Cervical spine injuries in children are usually seen in the upper cervical region owing to the unique biomechanics and anatomy of the pediatric cervical spine. Knowledge of the normal embryologic development and anatomy of the cervical spine is important to avoid mistaking synchondroses for fractures in the setting of trauma. Familiarity with anatomic variants is also important for correct image interpretation. These variants include pseudosubluxation, absence of cervical lordosis, wedging of the C3 vertebra, widening of the predental space, prevertebral soft-tissue widening, intervertebral widening, and "pseudo–Jefferson fracture." In addition, familiarity with mechanisms of injury and appropriate imaging modalities will aid in the correct interpretation of radiologic images of the pediatric cervical spine.

Abbreviations: ADI = atlantodens interval, SCIWORA = spinal cord injury without radiographic abnormality, 3D = three-dimensional

Index terms: Spine, anatomy, 31.92 • Spine, CT, 31.1211 • Spine, diseases • Spine, dislocation, 31.42, 31.4211 • Spine, fractures, 31.41 • Spine, injuries • Spine, MR, 31.1214 • Spine, radiography, 31.11

RadioGraphics 2003; 23:539–560 • **Published online** 10.1148/rg.233025121

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Introduction

The interpretation of cervical spine images can be challenging even for the most experienced radiologist. Radiologic evaluation of the pediatric cervical spine can be even more challenging due to the wide range of normal anatomic variants and synchondroses, combined with various injuries and biomechanical forces that are unique to children. Although a child can be defined radiographically as an individual with open epiphyses, this definition is not applicable in the cervical spine. By the time a child is 8–10 years old, the cervical spine reaches adult proportions (1,2). After the age of 10–12 years, the clinical sequelae of pediatric and adult trauma are similar (3). In this article, we review the normal anatomy and variants of the pediatric cervical spine. We also discuss and illustrate cervical spine injuries that occur in the pediatric population.

Epidemiologic Considerations

The reported prevalence of spinal injuries ranges from one to five cases per 100,000 persons; over one-half of these injuries include fractures of the cervical spine (4–6). Cervical spine injuries are less common in children than in adults, with 1%–2% of pediatric trauma victims requiring hospitalization (7). Approximately 72% of spinal injuries in children under 8 years old occur in the cervical spine (3). The anatomy of the developing cervical spine predisposes children to injury of the upper cervical spine. In general, the younger the child, the more likely an upper cervical spine injury will occur. Because of their unique anatomy, younger children tend to have more injuries located from the occiput to the C2–C3 vertebral level. These injuries are also associated with a high risk of neurologic damage, with a 25%–50% prevalence of associated head injuries (5–9).

Causes of Injury

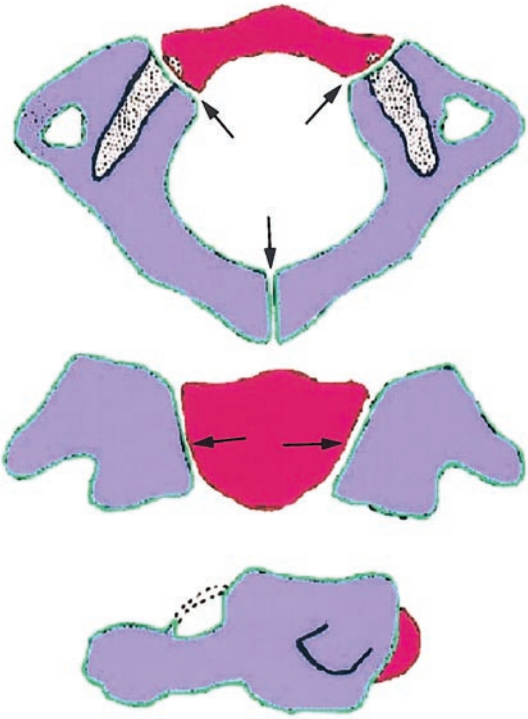
Mechanisms of injury also differ depending on the age of the patient. In children under 8 years old, 25%–60% of injuries occur secondary to motor vehicle accidents, including events in which the victim was a passenger, pedestrian, or bicyclist (5–8,10–14). Falls and sports-related injuries tend to occur in older children. Less common injuries can be seen secondary to birth trauma; these injuries are most commonly associated with breech deliveries (3,13). Cervical spine injury from child abuse or nonaccidental causes are also seen on occasion (12,13,15). In addition, underlying conditions such as Down syndrome, Morquio syndrome, Grisel syndrome, and rheumatoid arthritis may predispose to congenital anomalies of the vertebrae and ligamentous laxity. Thus, affected patients may be predisposed to C1-C2 subluxations and instability (13,17).

Embryologic Development and Normal Anatomy

Evaluation of the pediatric cervical spine often becomes problematic because of the unique radiologic anatomy of children. Epiphyseal variants, unique vertebral architecture, incomplete ossification of synchondroses and apophyses, and hypermobility may all cause the radiologist to feel uncertain when interpreting images obtained in a child with a history of injury, pain, and stress. Therefore, familiarity with normal anatomy can help avoid misinterpretation of normal epiphyses and anatomic variants as pathologic conditions. Generally, epiphyseal plates are smooth and regular, are seen in predictable locations, and have sclerotic lines. In contrast, fractures occur in unpredictable locations and are irregular and nonsclerotic.

The first two cervical vertebrae are unique in their development. C1, or the atlas, is formed by three primary ossification sites: the anterior arch and the two neural arches (Fig 1), which surround the anterior arch and fuse later in life to form the posterior arch. The anterior arch is ossified in only 20% of cases at birth and becomes visible as an ossification center by 1 year of age. The neural arches appear in the 7th fetal week. The anterior arch fuses with the neural arches by 7 years of age; before this, "nonfusion" may be mistaken for a fracture (16–20). The neural arches fuse posteriorly by 3 years of age. Occasionally, the anterior ossification center of C1 does not develop and the neural arches attempt to fuse anteriorly. This fusion abnormality can be differentiated from a fracture in that it demonstrates sclerotic margins (21).

C2, or the axis, has the most complex and unique development of all vertebrae. There are four ossification centers at birth: one for each neural arch, one for the body, and one for the odontoid process (Fig 2). The odontoid process



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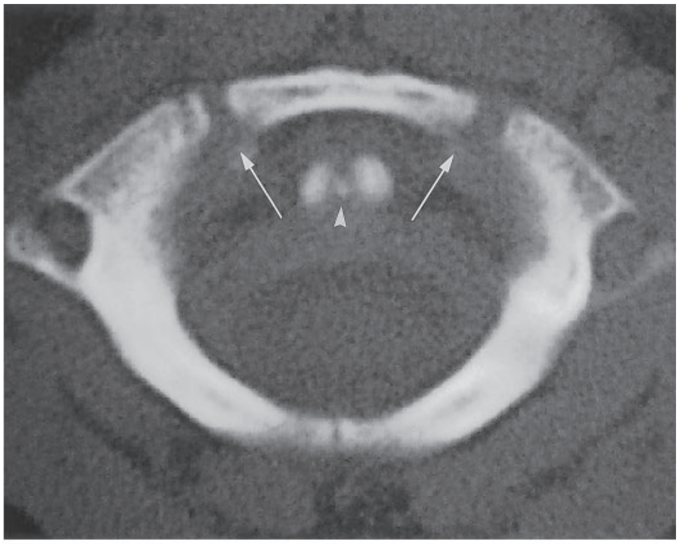
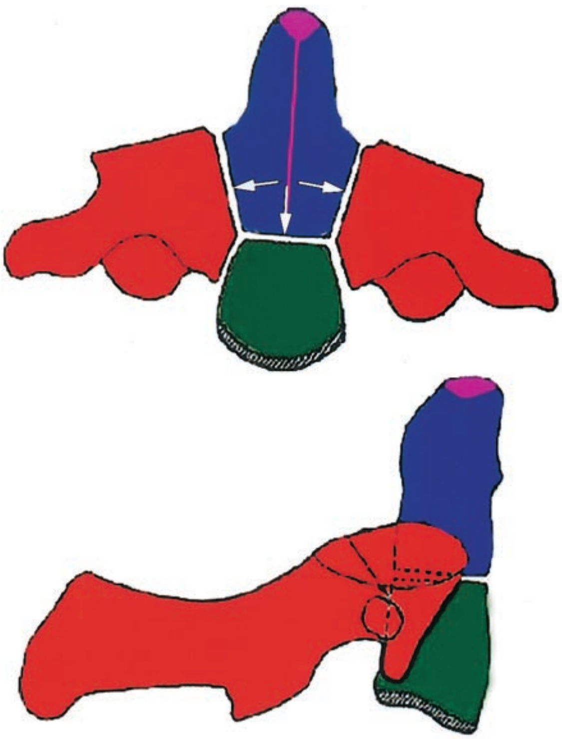


b.

Figure 1. Drawings **(a)** and axial computed tomographic (CT) scan **(b)** through C1 in an infant show the ossification centers of C1 with open synchondroses (arrows). Note the segmented tip of the dens (arrowhead in **b**).



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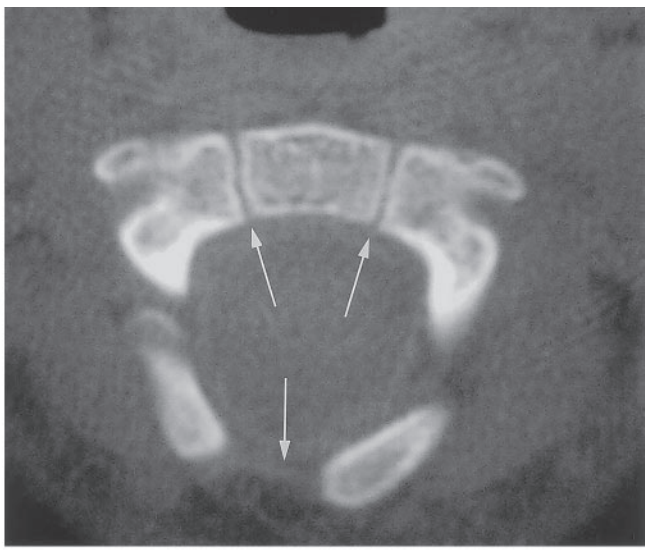

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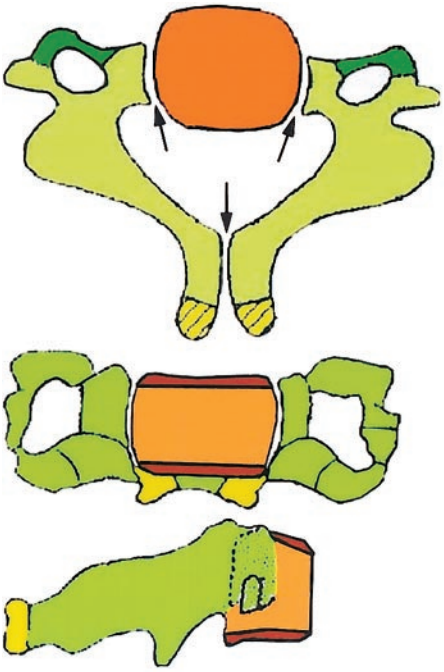
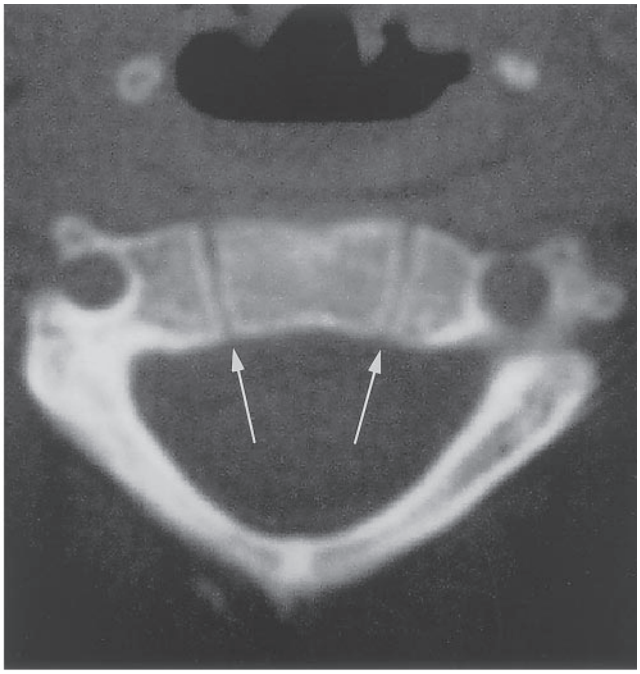
Figure 2. Drawings **(a)** and axial CT scan **(b)** through C2 in an infant show the ossification centers of C2 with open synchondroses (arrows).



a.



b.

Figure 3. Drawings **(a)** and axial CT scan **(b)** through C3 in an infant show the ossification centers of C3 with open synchondroses (arrows).

forms in utero from two separate ossification centers that fuse in the midline by the 7th fetal month. A secondary ossification center appears at the apex of the odontoid process (os terminale) between 3 and 6 years of age and fuses by age 12 years. The body of C2 fuses with the odontoid process by 3–6 years of age. This fusion line (subdental synchondrosis), or the remnant of the cartilaginous synchondrosis, can be seen until age 11 years and may be confused with a fracture. The neural arches fuse posteriorly by 2–3 years of age and with the body of the odontoid process between 3 and 6 years of age (16,17,19,20,22).

C3 through C7 can be discussed as a unit because they exhibit the same developmental pattern. Three ossification sites are present: the body, which arises from a single ossification site, and the two neural arches (Fig 3). The neural arches fuse posteriorly by age 2–3 years, and the body fuses with the neural arches between 3 and 6 years of age. Additionally, secondary ossification centers may be seen at the tips of the transverse processes and spinous processes that may persist until early in the 3rd decade of life and simulate fractures. Secondary ossification centers can also appear at the superior and inferior aspects of the cervical vertebral bodies and remain unfused until early adulthood (Fig 4) (1,16,17,19,20).

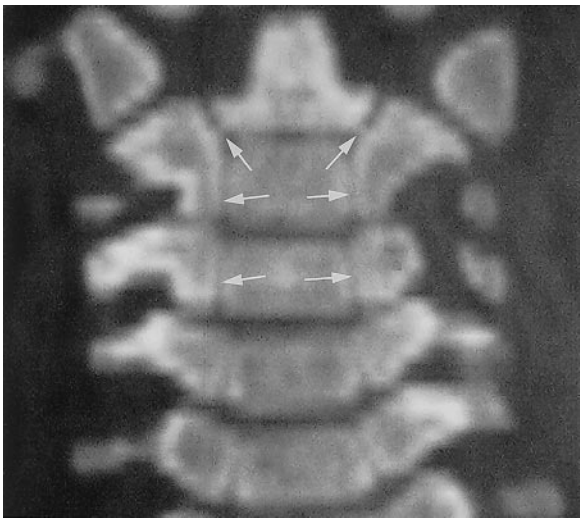
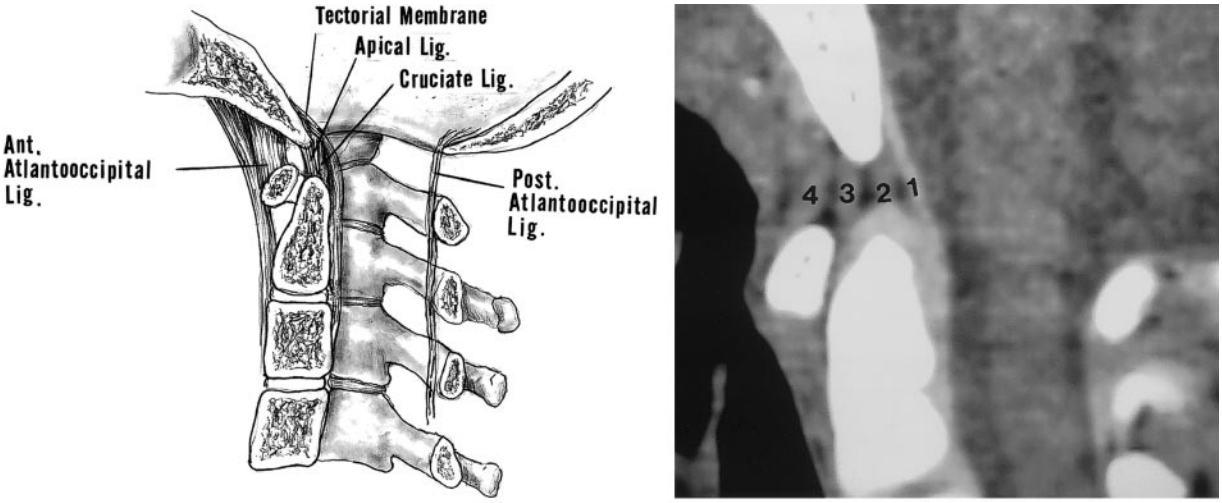


Figure 4. Coronal reformatted CT scan of the cervical spine in an infant shows open synchondroses (arrows).



a. b.

Figure 5. Drawing **(a)** and sagittal reformatted CT scan **(b)** of the upper cervical spine show the normal ligamentous anatomy and atlanto-occipital articulation. *1* = tectorial membrane, *2* = apical ligament, *3* = atlanto-occipital ligament, *4* = anterior longitudinal ligament.

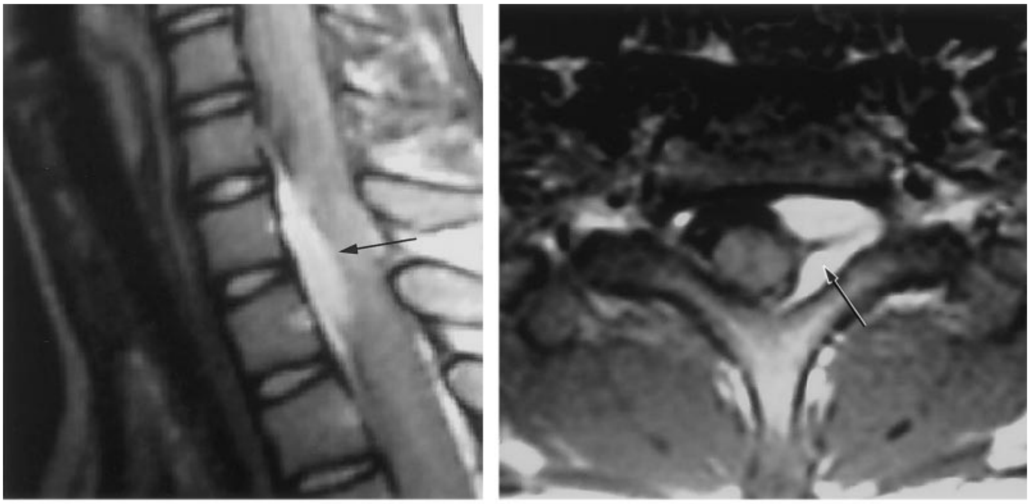
In addition to knowledge of the normal development of the upper cervical spine, familiarity with the normal anatomy and ligaments of the craniocervical junction (Fig 5) is important for understanding mechanisms of injury. The anterior and posterior atlanto-occipital membranes extend from the upper aspect of C1 to the anterior and posterior aspects of the foramen magnum. The anterior atlantoaxial ligament extends from the anterior midportion of the dens to the inferior aspect of the anterior arch of C1. The tectorial membrane is the superior extension of the posterior longitudinal ligament and attaches to the anterolateral aspect of the foramen magnum. The transverse ligament extends from the tubercle on the inner aspect of one side of the atlas to the tubercle on the other side. The apical ligament lies between the superior longitudinal fasciculus of the cruciform ligament and the anterior atlanto-occipital membrane. The alar ligaments connect the lateral aspect of the dens and the medial inferior aspect of the occipital condyles. The main function of the alar ligaments is to limit rotation to the contralateral side. Hence, an alar ligament tear results in a higher range of motion to the contralateral side. Rotational instability may result from this type of injury (16,19, 20,23).

Pediatric Versus Adult Cervical Spine

Cervical spine injuries in children usually occur in the upper cervical spine from the occiput to C3. This fact may be explained by the unique biomechanics and anatomy of the pediatric cervical spine. The fulcrum of motion in the cervical spine in children is at the C2-C3 level; in the adult cervical spine, the fulcrum is at the C5-C6 level (11,13). The immature spine is hypermobile because of ligamentous laxity, shallow and angled facet joints, underdeveloped spinous processes, and physiologic anterior wedging of vertebral bodies, all of which contribute to high torque and shear forces acting on the C1-C2 region. Incomplete ossification of the odontoid process, a relatively large head, and weak neck muscles are other factors that predispose to instability of the pediatric cervical spine (6,13,17,19,20,24,25).

Imaging Evaluation

A history of head or facial trauma, loss of consciousness, injury sustained in a high-speed motor vehicle accident, or birth trauma is an indication for clinical evaluation of the cervical spine. This evaluation should include a complete physical



a. b.

Figure 6. Sagittal **(a)** and axial **(b)** T1-weighted MR images through the cervical spine of a 7-year-old girl who experienced minor trauma show a hyperintense epidural hematoma at the C7-T1 level (arrow). The spinal cord is displaced to the right.

and radiologic examination. Unexplained hypotonia or hypertonia or abnormal neurologic examination findings in the setting of minor trauma are also relative indications for imaging of the cervical spine. The most common symptoms of cervical spine injury are pain and torticollis. Neck or occipital pain that radiates to the shoulders and popping or snapping of the neck with or without pain may suggest the presence of a cervical spine injury. Palpation of the neck may reveal local tenderness, muscle spasm, or contracture and asymmetry. For initial radiographic screening, lateral, anteroposterior, and odontoid views of the cervical spine should be obtained (3,10,17,24,26–29).

Recently, the need for the odontoid view has been questioned. Some experts believe that a lateral radiograph may be sufficient for evaluation of children under 5 years old (30,31). If the patient is medically unstable, cross-table lateral radiography may be performed until the patient's condition permits complete evaluation of the cervical spine. The false-negative rate for a single cross-table lateral radiograph ranges from 21% to 26%; therefore, complete evaluation with either conventional radiography or CT is necessary (2,32,33). CT with multiplanar reformatting has a crucial role in the assessment of cervical spine injury. CT shows the exquisite bone detail of the cervical spine and demonstrates fractures and the extent of bone injury far better than does magnetic resonance (MR) imaging. Multidetector CT allows fast acquisition of thin-section images with resultant increased spatial resolution and decreased need for sedation. MR imaging is especially helpful in the evaluation of trauma-related spinal cord injury (Fig 6). MR imaging facilitates evaluation of the extradural spaces and of the integrity of the spinal ligaments. Increased intraspinous distance, divergence of the articular processes, and widening of the posterior aspect of the disk space are indicative of pediatric cervical spine instability.

Figure 7. Lateral radiograph of the cervical spine in a 2-year-old girl shows an increased but still normal atlantoaxial distance (arrow). Note that the widened prevertebral soft-tissue component is also normal.

Normal Radiographic Parameters and Variants of the Pediatric Cervical Spine

There are several normal anatomic variants that may be encountered during imaging of the pediatric cervical spine. One must be cognizant of these variants to avoid confusing them with pathologic conditions.

The atlantodens interval (ADI) is defined as the distance between the anterior aspect of the dens and the posterior aspect of the anterior ring of the atlas. This distance should be 5 mm or less. In the adult population, the normal ADI is 3 mm. In patients with a normal ADI, the transverse atlantal ligament and the alar ligament will be intact (Fig 7). An ADI that exceeds 5 mm in lateral flexion and 4 mm in lateral extension indicates instability and is suspicious for ligamentous disruption (13,20,34,35).

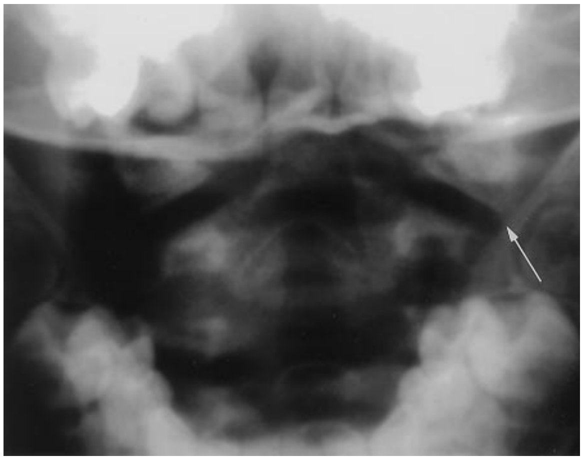


Figure 8. Open-mouth radiograph demonstrates a pseudo–Jefferson fracture with pseudospread of the atlas on the axis (arrow).

Pseudospread of the atlas on the axis (“pseudo–Jefferson fracture”) can be seen on anterior open-mouth radiographs (Fig 8). Up to 6 mm of displacement of the lateral masses relative to the dens is common in patients up to 4 years old and may be seen in patients up to 7 years old (13,20,36). On extension radiographs, overriding of the anterior arch of the atlas onto the odontoid process can be seen in 20% of healthy children (13,20,23).

In children, the C2-3 space and, to a lesser extent, the C3-4 space have a normal physiologic displacement (3,13,19,20,37,38). In some cases, this displacement is so profound that it can resemble a true injury. In a study involving 160 pediatric patients with no history of cervical spine trauma, 46% of children less than 8 years old had pseudosubluxation of C2 on C3 on lateral flexion and extension radiographs of the cervical spine (23). The posterior cervical line is a line that is

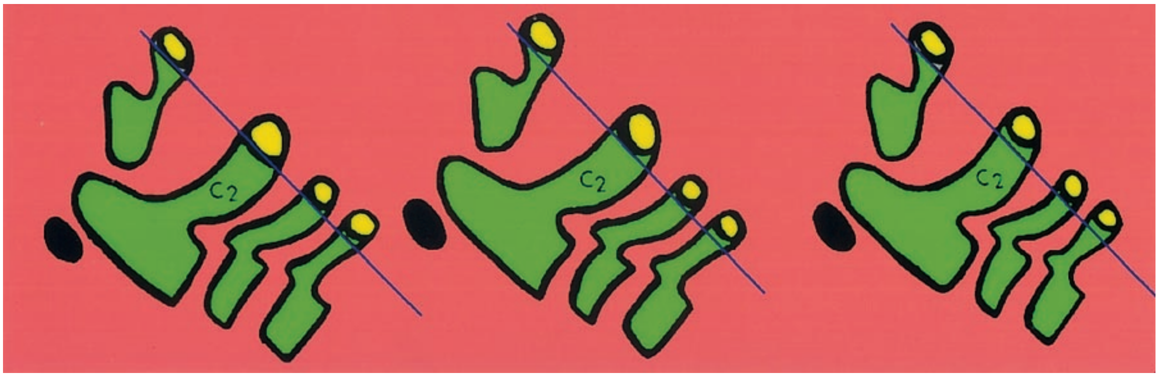


Figure 9. Drawings illustrate the posterior cervical line and show that the anterior edges of the spinous processes of C1, C2, and C3 should line up within 1 mm of each other in both flexion and extension. (Reprinted, with permission, from reference 20.)

drawn from the anterior aspect of the spinous process of C1 to the anterior aspect of the spinous process of C3 (Fig 9). The anterior edges of the spinous processes of C1, C2, and C3 should line up within 1 mm of each other on both flexion and extension radiographs. If this line does not overlap the anterior aspect of the spinous process of C2 by 2 mm or more, a true injury is present (Fig 10) (20). An abnormal posterior cervical line measurement often indicates the presence of a bilateral pars interarticularis ("hangman fracture") of C2.

The absence of lordosis, although potentially pathologic in an adult, can be seen in children up to 16 years of age when the neck is in a neutral position (3,13,23,39). The normal posterior intraspinous distance is a good indicator of ligamentous integrity and should not be more than 1.5 times greater than the intraspinous distance one level either above or below the level in question. In children, the flexion maneuver can increase the distance between the tips of the C1 and C2 spinous processes. This widened C1-2 intervertebral distance is a normal finding and should not be misinterpreted as ligamentous injury (20,39,40). This finding is postulated to be secondary to the tight ligamentous attachment between the skull base and C1.

Ossification centers such as secondary centers of ossification of spinous processes and unfused ring apophyses of vertebral bodies can be confused with fractures. Normal physeal plates should be recognized as smooth, regular structures with subchondral sclerotic lines. Acute fractures are irregular, are not sclerotic, and can occur at any location. The posterior ring of C1 can remain cartilaginous (13,18,41). The apical odontoid epiphysis is visualized at radiography in 26% of children between 6 and 8 years of age and should not be confused with fracture (13,23,39). In early infancy, cervical vertebral bodies have an oval appearance. These vertebrae take on a more rectangular appearance with advancing age. Anterior wedging of up to 3 mm of the vertebral bodies should not be confused with compres-

Figure 10. Lateral radiograph of the cervical spine in a pediatric patient shows pseudosubluxation at the C2-C3 level (arrow).

Figure 11. Lateral radiograph of the cervical spine in a pediatric patient shows normal anterior wedging of multiple cervical vertebral bodies, most prominently at the C3 level (arrow).

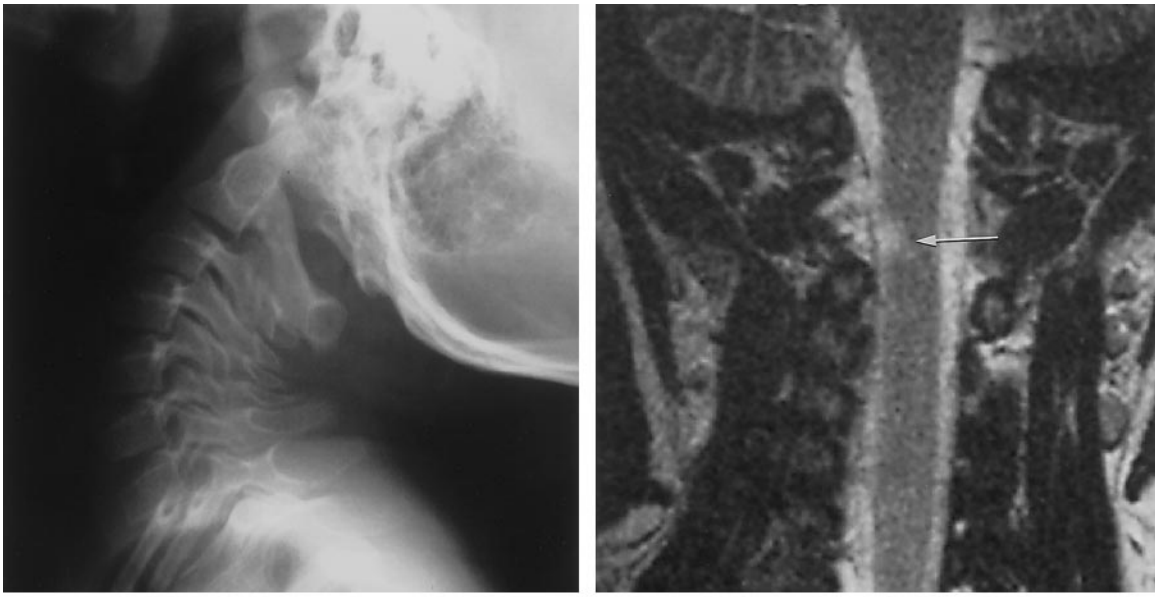
sion fracture (13,23,39). Such wedging can be profound at the C3 level (Fig 11), with deformity of the vertebral body ossification center as its anterosuperior corner (42). This finding has been postulated to occur secondary to hypermobility of the spine. As the child matures, this wedging deformity resolves, and a normal vertebra is seen.

Prominence of the prevertebral soft tissues on lateral radiographs of the cervical spine in adults is often due to edema or hemorrhage caused by adjacent cervical spine injury. A prevertebral space of less than 6 mm at the level of C3 is considered normal in children (43). In pediatric patients, widening of the prevertebral soft tissues can be a normal finding that is related to expiration. When lateral radiography of the cervical spine in an infant with possible spinal injury shows wide prevertebral soft tissues, repeat lateral radiography in mild extension and in inspiration should be performed to determine if the apparent soft-tissue abnormality is real.

Types of Cervical Spine Injuries

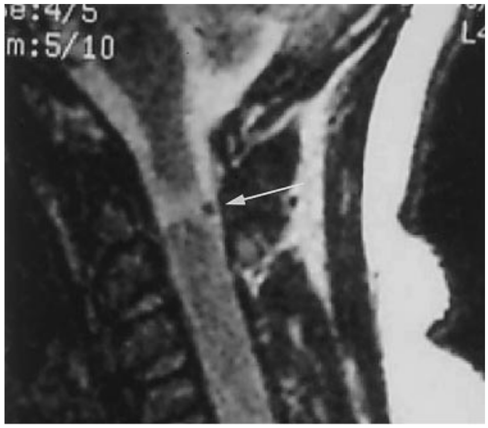
Spinal Cord Injury without Radiographic Abnormality

Spinal cord injury without radiographic abnormality (SCIWORA) is defined as a spinal cord injury with no abnormality depicted at conventional radiography or CT (45). Normal cervical spine radiographs obtained in patients with cervical spine injury are likely related to a transient ligamentous deformation of the cervical spinal column. The spinal cord can be severely disrupted, even on apparently normal radiographs. A possible explanation for SCIWORA is related to the difference in elasticity between the spinal column and the spinal cord: The less elastic spinal cord is more prone to injury when deformed (11,46–50). The other suggested cause of SCIWORA is ischemia that results from direct



a. b.

Figure 12. **(a)** Lateral extension radiograph of the cervical spine shows normal bone alignment. **(b, c)** Coronal **(b)** and sagittal **(c)** T2-weighted MR images of the cervical spine show normal bone alignment but focal increased signal intensity in the upper cervical spinal cord (arrow), a finding that is consistent with edema or hemorrhage of the cord (SCIWORA).



c.

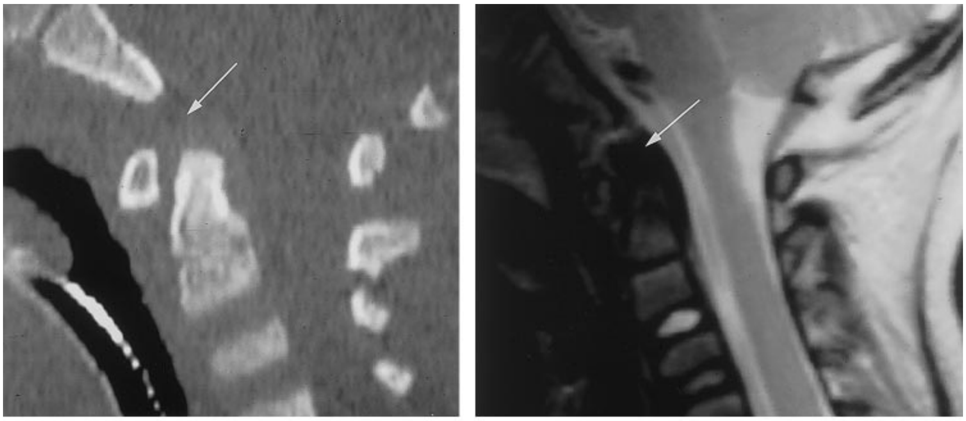
vessel injury to or hypoperfusion of the spinal cord parenchyma (50,51). MR imaging should be performed to evaluate for spinal cord injury when clinical findings are present despite the absence of radiographic abnormalities (13,49–52). The prognosis depends on the degree of spinal cord injury (Fig 12).

Occiput-C1 Injury

Despite the reports of affected individuals who survived with no neurologic injury, craniocervical junction injuries are often fatal, and there are severe neurologic sequelae. Sudden deceleration causes sudden craniovertebral dislocation and reduction. Deployment of air bags has also been associated with craniocervical junction injury (53). Although atlanto-occipital dislocation is uncommon, it is 2.5 times more prevalent in young children than in adults (21,54,55). Young children are more vulnerable to this injury due to small occipital condyles and horizontally oriented atlanto-occipital joints. The atlanto-occipital articulation is therefore less stable in young children than in adults (13). There is injury or rupture of the tectorial membrane and the alar ligaments (Fig 13), which allows motion of the cranium relative to the spine (13,46,56–61). This injury is diagnosed radiographically on the basis of excessive mobility of the occiput on C1 with increased distance and malalignment. Radiographic evaluation of the craniocervical junction can be difficult owing to the rotation and superimposition of structures. The evaluation of this injury with CT is crucial, and sagittal reformatted images should always be obtained (Fig 14), including images of the atlanto-occipital articulations bilaterally.

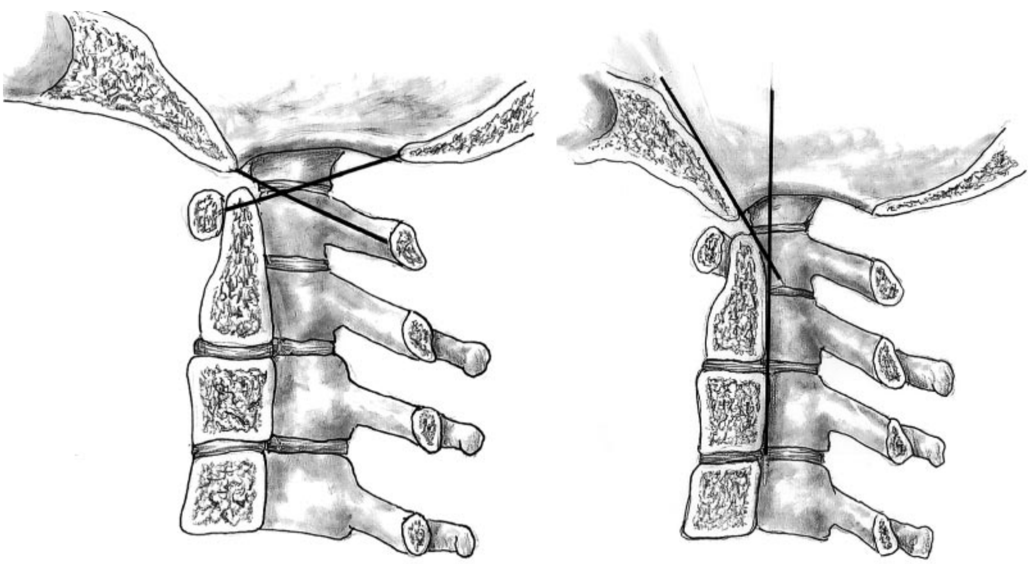
Several methods of evaluating craniocervical junction injury on lateral radiographs have been described. A gap of more than 5 mm between the occipital condyles and the condylar surface of the atlas is highly suggestive of craniocervical injury (13,57,58). Another method that is often used to evaluate the craniocervical junction is the Wachenheim clivus line, a line drawn along the posterior aspect of the clivus toward the odontoid process (Fig 15a). An abnormality is suspected when this line does not intersect or is tangential to the odontoid process (13,21,59). The Powers ratio is the ratio of the distance from the basion

Figure 13. Sagittal T2-weighted MR image of the cervical spine in a pediatric patient shows a C2 fracture with disruption of the tectorial membrane (arrow), findings that indicate a severe and unstable injury.



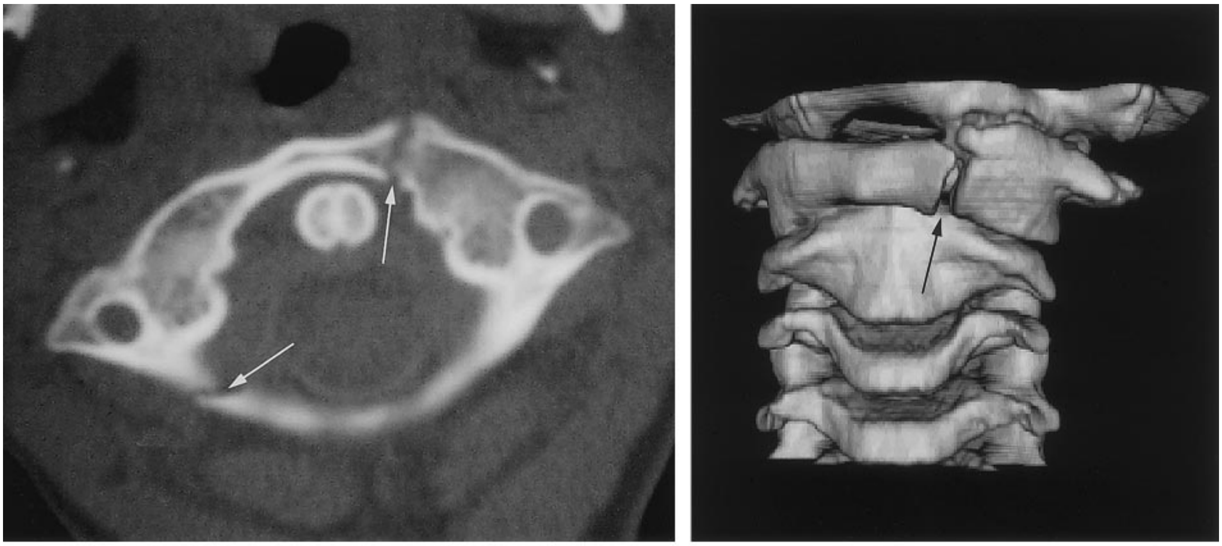
a. b.

Figure 14. **(a)** Sagittal reformatted CT scan demonstrates a false-positive finding of increased C2-occiput distance (arrow). **(b)** Sagittal T2-weighted MR image reveals incomplete ossification of the dens (arrow), which led to the false-positive finding in **a**.



a. b.

Figure 15. Drawings illustrate the Wachenheim clivus line **(a)** and the Powers ratio **(b)**, two different methods for evaluating craniocervical junction injury.



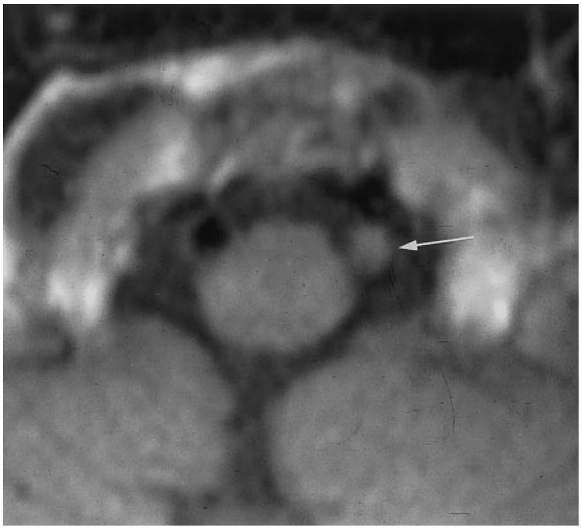
a. b.

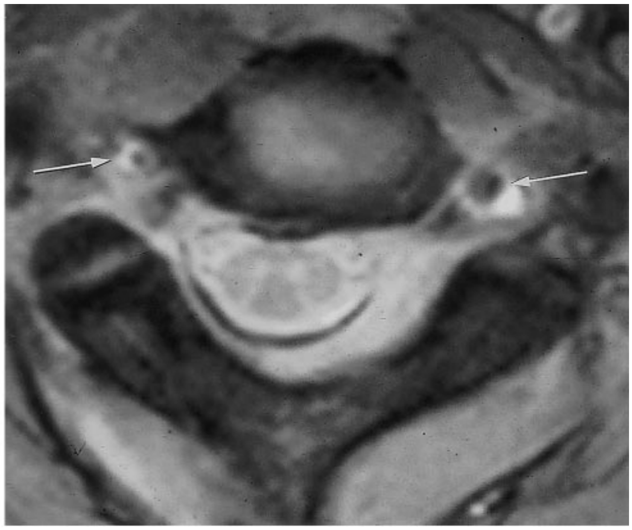
Figure 16. Axial CT scan through C1 **(a)** and three-dimensional (3D) reformatted CT scan of the upper cervical spine **(b)** obtained in a 6-year-old boy show anterior and posterior ring fractures of C1 (arrows).

(the tip of the clivus) to the posterior aspect of the spinolaminar line of the atlas divided by the distance from the anterior tubercle of the atlas to the lip of the foramen magnum (Fig 15b). This ratio should be less than 1 in healthy individuals (13, 58). The distance between the basion and the tip of the odontoid process should be 12 mm or less, and a line drawn superiorly from the posterior aspect of the body of C2 should come within 12 mm of the basion (Fig 15) (13,59). There is usually significant prevertebral soft-tissue swelling associated with craniocervical injury, and damage to the brainstem and upper cervical spinal cord may also occur. Other clinical findings include damage to the upper cervical and lower cranial nerves (57). Craniocervical injury is often fatal (62). However, in patients who survive the injury, treatment consists of fusion of the occiput to either C1 or C2. Fractures of the occipital condyles are extremely rare, and CT with multiplanar reformatting clearly depicts these fractures.

Fractures of the Atlas

Jefferson fracture, or fracture of the ring of C1, is caused by axial loading injury, with force transmitted through the lateral occipital condyles to the lateral masses (13,35). Fractures usually occur through the anterior and posterior arches of C1 (Fig 16) (63). A Jefferson fracture usually manifests as asymmetry between the odontoid process and the lateral masses on an open-mouth odontoid image. These fractures are stable if the transverse ligament is intact (35). However, when the transverse ligament is ruptured, there is increased distance between the lateral masses and the odontoid process. A distance of 6 mm or more between the lateral mass of C1 and the odontoid process is suggestive of ligamentous disruption (35,44,57,64). In addition, a reduced anteroposterior diameter of the cervical spinal canal as seen on a lateral radiograph or a sagittal two-dimensional reformatted CT scan is often associated with spinal cord injury. Isolated fractures of the anterior or posterior arch of C1 may also occur (65–67).





a. b.

Figure 17. **(a)** Axial T1-weighted MR image obtained at the level of the craniocervical junction shows loss of normal flow void in the left vertebral artery (arrow). **(b)** Axial T2-weighted MR image through the upper cervical spine shows bilateral vertebral artery dissection (arrows).

Atlantoaxial Injuries

Traumatic ligamentous disruption, rotatory subluxation, and odontoid separation can occur as a result of C1-C2 injury. Although under normal circumstances there is minimal rotation between the occiput and C1, 50% of cervical rotation occurs between the C1 and C2 articulation (68). Approximately one-third of the cervical spine diameter is occupied by the odontoid process, one-third by the spinal cord, and one-third by the subarachnoid space. These dimensions afford the spinal cord a margin of safety during excessive motion of the upper cervical spine (69). When rotation of the cervical spine exceeds its normal limits, the odontoid process can injure the spinal cord and adjacent structures such as the vertebral artery (Fig 17).

Atlantoaxial Rotatory Subluxation.—Atlantoaxial rotatory subluxation is a cause of torticollis and can occur either spontaneously, as a result of trauma, or in association with underlying congenital abnormalities. Other disorders that may cause childhood torticollis include infections, spinal cord tumors, and an underlying abnormality within the sternocleidomastoid muscle (3,70). Atlantoaxial subluxation is a rotational disorder of the atlantoaxial joint that results in either limited rotation of the neck or, in rare cases, fixation. The anterior facet of C1 becomes locked on the facet of C2, which causes impaired rotation at this joint (20,68,70,71). Atlantoaxial subluxation may occur with or without C1-C2 dislocation. Some investigators view rotatory subluxation and dislocation as different manifestations of the same injury. However, in rotatory dislocation, there is anterior displacement of the lateral mass of C1 relative to C2 (Fig 18). Furthermore, the alignment abnormality of C1 on C2 is more pronounced, which results in widening of the predental space. Rotatory subluxation is accompanied by a normal ADI

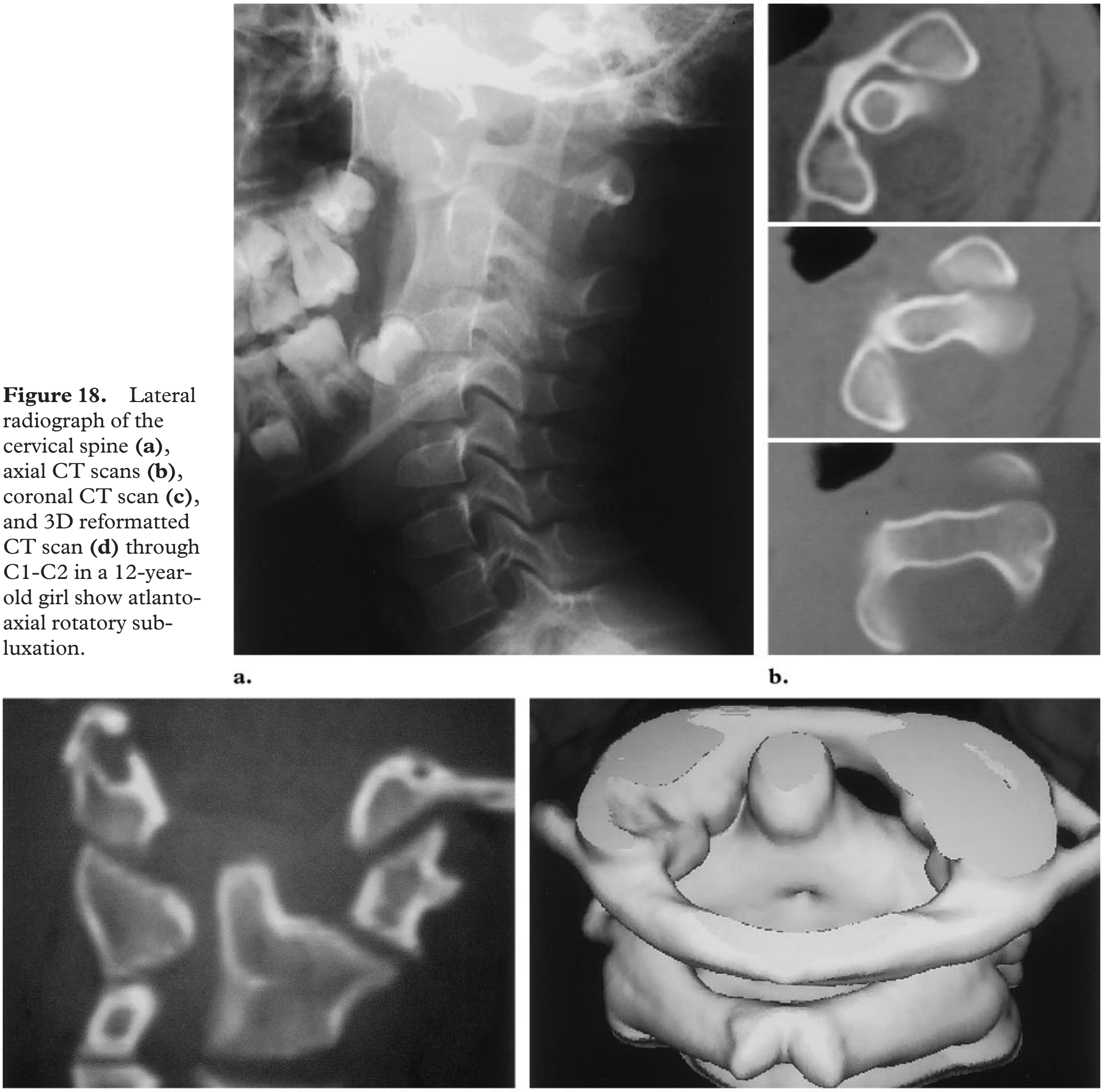


Figure 18. Lateral radiograph of the cervical spine **(a)**, axial CT scans **(b)**, coronal CT scan **(c)**, and 3D reformatted CT scan **(d)** through C1-C2 in a 12-year-old girl show atlantoaxial rotatory subluxation.

a. b. c. d.

(20). At lateral radiography, there may be loss of definition of the craniocervical junction, and the anterior arch of C1 is not oriented in a true lateral plane. Additionally, one lateral mass of C1 rotates forward and appears wider and closer to the midline (20), whereas the other is narrower and farther away from the midline. These findings may be seen in healthy patients with marked head rotation or any cause of torticollis. Again, a normal ADI implies no displacement.

In atlantoaxial fixation, the normal rotation of C1 on C2 cannot occur, and the abnormal relationship between the atlas and the axis becomes fixed. The cause of atlantoaxial rotatory fixation is not known. Fielding and Hawkins (72) have classified atlantoaxial rotatory subluxation into four categories (Fig 19). Type I, the most common type, demonstrates no displacement of C1; type II demonstrates 3–5 mm of anterior displacement of C1 and is associated with abnormality of the transverse ligament; type III demonstrates over 5 mm of anterior displacement of C1 on C2 and is associated with deficiency of the transverse and alar ligaments; and type IV, a rare entity, demonstrates C1 displacement posteriorly.

To differentiate fixation from rotatory subluxation or displacement without fixation, dynamic CT may be performed to demonstrate that C1

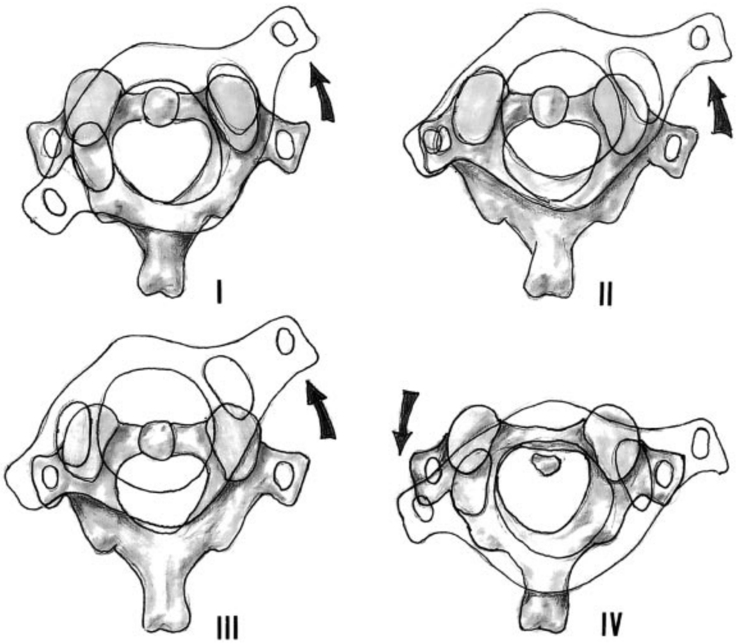
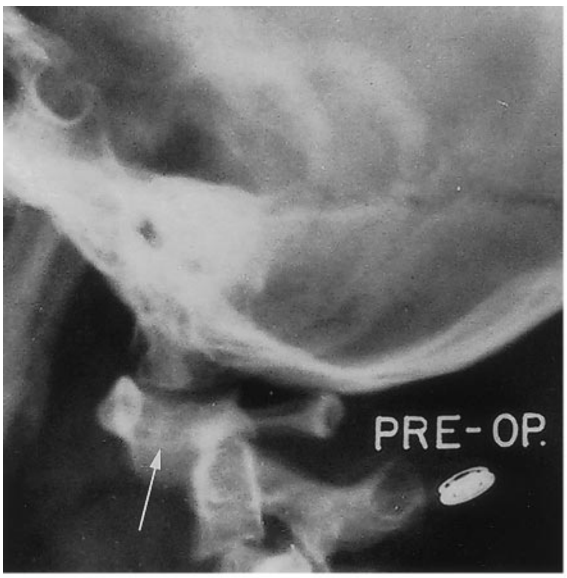


Figure 19. Drawings illustrate the Fielding classification scheme for atlantoaxial rotatory fixation. Type I demonstrates no displacement of C1, type II demonstrates 3–5 mm of anterior displacement of C1 and is associated with abnormality of the transverse ligament, type III demonstrates over 5 mm of anterior displacement of C1 on C2 and is associated with deficiency of the transverse and alar ligaments, and type IV demonstrates C1 displacement posteriorly. Arrows indicate direction of movement.



20.

21.

Figures 20, 21. **(20)** Lateral radiograph of the cervical spine in a 16-year-old girl with a history of Down syndrome demonstrates atlantoaxial subluxation (arrow). **(21)** Lateral radiograph of the cervical spine in an 18-year-old man who had died from injuries sustained in a motor vehicle accident shows pronounced atlantoaxial disruption.

and C2 are fixed as a single unit (13,68,73–77). This study may be performed if the rotational abnormality does not resolve on its own or with conservative treatment. In dynamic CT, an initial study is obtained with the patient at rest, after which scanning is repeated with voluntary contralateral rotation of the patient's head. In fixation, C1 and C2 become a fixed unit and cannot rotate independently. Some investigators have advocated performing dynamic CT with the patient under general anesthesia to facilitate muscle relaxation for diagnosis (78).

Ligamentous Disruption of the Atlantoaxial Joint.—Displacement of C1 on C2 of more than 5 mm between the anterior cortex of the dens and the posterior cortex of the anterior ring of C1 suggests ligamentous injury at the atlantoaxial articulation (Figs 20, 21) (13,17,21,34,35,64,66). Isolated transverse ligament injury is rare in healthy children, but chronic atlantoaxial instability can be seen in patients with rheumatoid diseases, bone dysplasias, and anatomic anomalies such as Klippel-Feil syndrome and os odontoideum

Figure 22. **(a, b)** Sagittal T1-weighted **(a)** and T2-weighted **(b)** MR images of the upper cervical spine show atlantoaxial dislocation. **(c, d)** Axial CT scan **(c)** and 3D reformatted CT scan **(d)** through the C1-C2 region show a small bone fragment (long arrow) between the anterior arch of C1 and the odontoid process, a finding that is consistent with os odontoideum. There is also an increased ADI. Note the unfused anterior arch of C1 (short arrow), which is a normal variant.

(3,13,17,35,79). These patients have an increased risk of developing neurologic injury with minor trauma. Necrotizing retropharyngeal infection and adenoidectomy can also cause disruption of the atlantoaxial ligaments.

Odontoid Fractures.—Odontoid fractures in children less than 7 years old most commonly occur through the cartilaginous synchondrosis (13,21). The synchondrosis is located below the level of the vascular supply to the lower dens; therefore, fractures to this area usually heal without the complications typically seen in adults, such as nonunion and pseudoarthrosis (43,80–82). Lateral radiographs usually demonstrate this fracture and the associated prevertebral soft-tissue swelling. The odontoid displacement is usually anterior, with the dens tilted posteriorly (20). CT may be used for diagnosis; however, because fractures are usually oriented in the axial plane, sagittal and coronal reformatted images are mandatory for evaluation and diagnosis. Anomalies of the odontoid process may also predispose patients to instability and injury. In cases of nonunion, the apical fragment of the dens will move cranially by the alar ligament; it will continue to be supplied with blood by the apical arcade vessels and will finally form the round ossicle called os odontoideum. The caudal portion of bone becomes avascular and resorbs. Os odontoideum may occur in a normal anatomic location or may be displaced (83). It is associated with instability of the atlantoaxial joint and cervical spinal cord injury (83,84). This instability can be visualized on lateral flexion-extension radiographs. Additional information is provided by CT and MR imaging (Figs 22, 23).

RadioGraphics

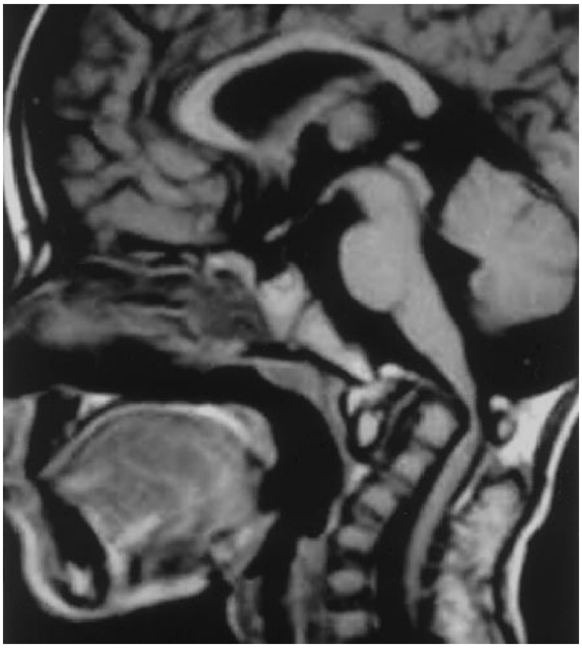


Figure 23. Sagittal midline T1-weighted MR image of the craniocervical junction shows an odontoid synchondral fracture and posterior dislocation of the upper cervical spine with spinal cord injury.

Figure 24. Lateral radiograph of the cervical spine in a 2-year-old girl with a history of nonaccidental trauma shows fracture through the pars interarticularis and posterior spinous process of C2 (arrow), a finding that is consistent with hangman fracture. Note the increased thickness of the prevertebral soft tissues.

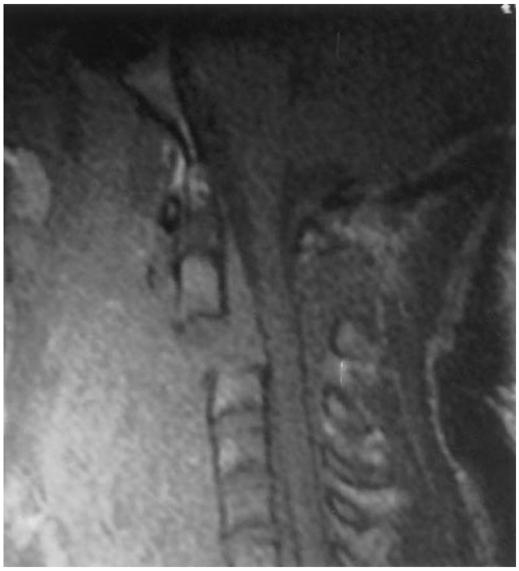


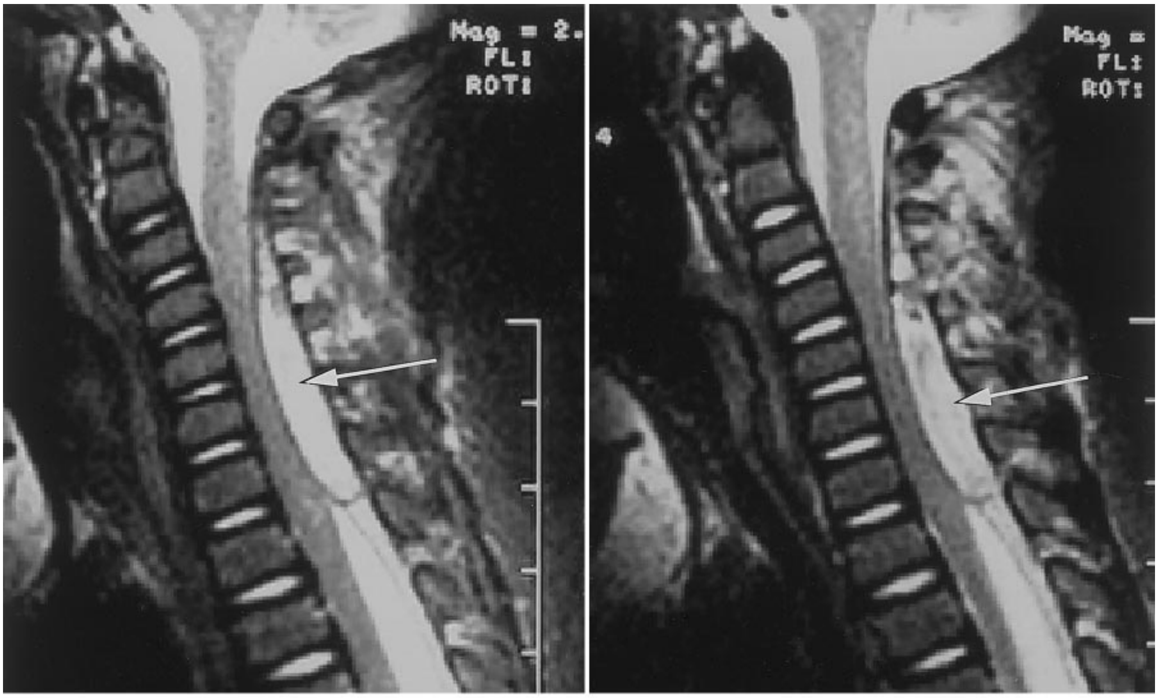
Figure 25. Sagittal T1-weighted MR image of the cervical spine shows a hangman fracture with ligamentous injury and extensive prevertebral and epidural hematoma.

Traumatic Spondylolisthesis of C2 (Hangman Fracture)

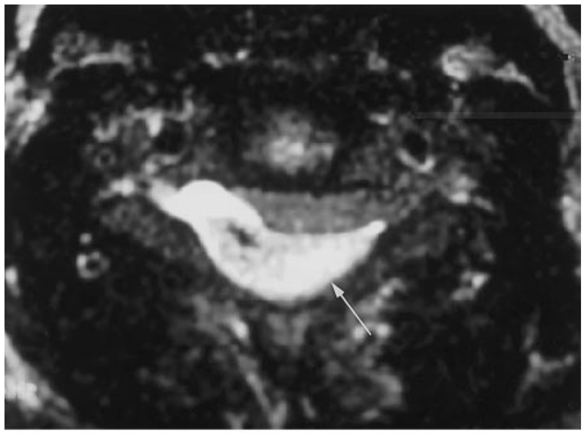
Hangman fracture is a hyperextension injury of the cervical spine. This fracture can occur in younger children but is less common than fractures of C1 and the odontoid process. Hangman fracture is associated with fractures through the pars interarticularis (13,85). Anterior subluxation of C2 on C3 with associated horizontal tearing of the C2-3 disk space may also be seen (Figs 24, 25) (85,86). This lesion can be diagnosed at lateral radiography, although CT and MR imaging may be useful for more detailed evaluation. It is important not to confuse this injury with the normal variant of pseudosubluxation.

Subaxial Injuries (C3–C7)

Subaxial injuries are more commonly seen in older children and may be secondary to sports-related injuries or injuries sustained in motor vehicle accidents.



a.



b.

Figure 26. Sagittal **(a)** and axial **(b)** T2-weighted MR images of the cervical spine show posterior epidural hematoma (arrow), which exerts mass effect on the spinal cord.

Posterior Ligamentous Injuries

Conventional radiography may demonstrate ligamentous injury; however, MR imaging is the modality of choice for evaluating ligamentous structures (Fig 26). Posterior ligamentous injuries usually require posterior fusion (87,88).

Wedge Compression Fractures

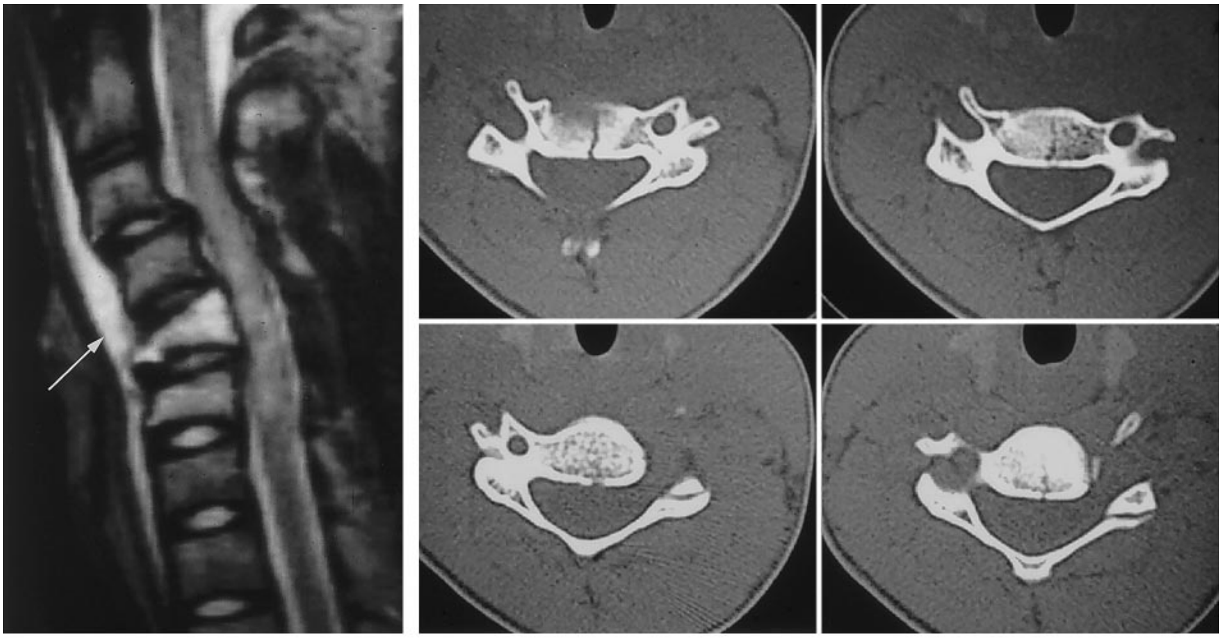
Given the greater resistance of the pediatric disk to herniation, wedge compression fractures are common and occur with flexion and concomitant axial loading, resulting in loss of vertebral height. These fractures are stable and heal easily. CT may be performed to evaluate for retropulsed bone fragments, and MR imaging may better delineate spinal cord contusions and ligamentous disruption (Fig 27) (88).

Facet Dislocations

Bilateral facet dislocations are unstable and are often associated with spinal cord syndromes. Radiographic findings include translational displacement of the adjacent vertebrae by 50% and dislocation of the facet joints (Fig 28). Facet dislocations can be associated with facet fractures, which are optimally identified with sagittal reformatted CT scans (89).

Late Sequelae of Cervical Spine Injuries

After a cervical spine injury, periodic follow-up is necessary for early recognition of possible sequelae such as kyphosis, scoliosis, and syrinx formation. Radiologic examination including CT and MR imaging is useful for assessing bone morphologic features and stability as well as spinal cord integrity (Fig 29).



a. b.

Figure 27. Sagittal T2-weighted MR image of the cervical spine **(a)** and axial CT scans through the C5 vertebra **(b)** show a compression fracture with prevertebral hematoma (arrow in **a**), with disruption of the anterior longitudinal ligament and extensive spinal cord contusion.

a. b.

Figure 28. Lateral radiograph **(a)** and sagittal T1-weighted MR image **(b)** of the cervical spine show bilateral facet dislocations of C4 on C5 (arrow).

Figure 29. Sagittal T1-weighted MR image of the upper thoracic spine shows atrophy of the spinal cord (arrow) due to previous injury sustained at birth during a breech delivery.

Conclusions

Knowledge of the normal development and morphologic features of the pediatric cervical spine can aid in the correct interpretation of imaging studies in the setting of trauma. Familiarity on the part of the radiologist with mechanisms of injury and appropriate imaging modalities will benefit any pediatric patient who undergoes radiologic evaluation.

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