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Pediatric Cervical Spine Trauma: Injury Patterns, Diagnosis, and Treatment

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Abstract

Background: Traumatic injuries to the cervical spine or spinal cord are uncommon pathologies in the pediatric population. As injury severity is disproportionately higher among children due to significant risk for debilitating long-term disability, traumatic spinal fractures in children raise greater clinical concern than comparable injuries in adults. ***Summary:*** Unlike adults, children possess unique features such as incomplete ossification of vertebrae, synchondroses, pseudo-subluxation, horizontal alignment of ligaments, and absence of lordosis, which results in greater mobility and flexibility in the pediatric spine. These features are prominent in the cervical spine, which accounts for the most common area of traumatic spinal injuries in children. ***Key Messages:*** In this review, we summarize injury patterns, diagnosis, and treatment of traumatic cervical spine injuries in the pediatric population.

Introduction

Traumatic injuries to the cervical spine or spinal cord are rare in the pediatric population. Overall, fractures of the spine account for fewer than 5% of all pediatric fractures [1], and the annual incidence of spinal column injury in children is estimated to be 93 per million population per year [2]. Spinal cord injury (SCI) is even less common, with an estimated incidence of 14–40 cases per million population per year [2]. As injury severity is disproportionately higher among children due to significant risk for debilitating long-term disability, traumatic spinal fractures in children raise greater clinical concern than comparable injuries in adults [3]. Traumatic brain injuries may also occur concurrently, and this lethal combination can contribute to higher mortality rates in children [4, 5].

Pediatric spines are susceptible to traumatic injury due to several anatomic elements that are intrinsic to the developing spine. These prominent features – which are distinct from the adult spine – include incomplete ossification of vertebrae, synchondroses, pseudo-subluxation, horizontal alignment of ligaments, absence of lordosis, anterior wedging of vertebral bodies, and pseudo-spread of the atlas/axis [6]. Collectively, these features translate to greater mobility and flexibility of the pediatric spine. By corollary, younger, actively growing

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children who have not fully developed their paraspinal musculature or completed osseous growth, possess more hypermobile spines that can place them at greater risk for permanent injury.

By virtue of their location, cervical spine injuries (CSIs) are perhaps the most feared subcategory of traumatic spinal injury. Damage to the cervical discoligamentous complex or bones of the cervical spine could potentially place the entire spinal cord or brainstem at risk [2, 7]. As such, early diagnosis and intervention are imperative to optimize recovery potential, and a comprehensive understanding of the proper diagnosis and management of pediatric CSI remains a high priority within the medical and surgical communities. In this article, we review injury patterns, diagnosis, and treatment of traumatic CSI in the pediatric population.

Epidemiology

Overall incidence of CSI in children is exceptionally low, with rates generally hovering around 1–2% of all traumatic injuries [8]. The majority of pediatric spinal fractures occur in the thoracolumbar spine, while 15–20% occur in the cervical spine [9, 10]. Although individual institutional rates of CSI may vary, queries of national registries indicate that these numbers are consistent. A study based on the National Pediatric Trauma Registry observed that only 1.5% of patients presenting with trauma were diagnosed with CSI, approximately 50% of which occurred specifically in the upper cervical spine [3]. Similarly, Lykissas et al. [10] found only 80 patients with cervical spine fractures when probing the National Electronic Injury Surveillance System database over a 10-year period (2003–2013). International studies have similarly reported a 1% rate of cervical spine fractures [11].

Two overarching epidemiological patterns are worth noting. The first pertains to mechanism of injury. Blunt trauma is often the primary cause of pediatric CSI, but there is a clear distinction of mechanism based on age. In children who are younger than 9 years old, home-related accidents, such as falls from standing position or from height, have been the most frequently causative mechanism [12]. In children between ages 10–16 years, sports and recreational accidents account for the majority of CSI [4, 12]. These patterns reflect the naturally changing habits and activity patterns of children as they age.

Second, CSI is more common among younger children. In children younger than 9 years of age, approximately half of all spinal injuries occur in the cervical spine whereas in older children, only a third do [13]. Puisto et al. [14] showed a similar dichotomy, with 64% of cervical injuries occurring in children under 9 years old and only 25% of injuries occurring in older children. Overall, the incidence of CSI in younger children has been reported to be as high as 15% [15].

Biomechanics

Spinal traumas often result in much more severe injuries in children compared to adults. This is due to a combination of anatomical differences: pediatric spines have a superior fulcrum, incomplete ossification of vertebrae and synchondrosis, ligaments more horizontally attached to articular bone surfaces, absence of lordotic curvatures, anterior wedging of vertebral bodies, pseudosubluxation, and pseudo-spread of atlas on axis [6]. Younger children in particular have hypermobile spines, leading to greater risk of injury to the spinal cord with flexion or extension injuries. In addition, with the proportionately larger head-to-body ratio seen in children, external forces can create a larger lever arm [16].

Anatomically, the upper cervical region is often the most unstable, especially at the craniovertebral junction [17]. In younger children, the craniovertebral junction is predisposed to greater degree of motion due to smaller occipital condyles, the flat orientation of the OC-C1 joint, larger head size resulting in a more superior fulcrum, and odontoid synchondrosis [16, 18, 19]. Underdeveloped muscles and ligamentous laxity – especially between C2/C3 – can also lead to hypermobility. In children younger than 8 years old, an unfused dentro-central synchondrosis increases the flexibility of the spine [17]. Thus, vigilance should be maintained when younger children present with confirmed or suspected traumatic injuries to the spine.

Subaxial hypermobility can also result due to facet joints that are more biased toward the axial plane, anterior wedging of the vertebral bodies that increase susceptibility to flexion forces, and more elastic joint capsules plus ligaments. Underdeveloped uncinate process also increase susceptibility to lateral or rotational forces. Degree of horizontal displacement in the subaxial spine is age-dependent. In children up to 8 years of age, translation up to 4.5 mm is considered normal; however, this threshold decreases to 3.5 mm for children above 8 years of age. Of note, literature suggests that the pediatric cervical spine begins to mature around age 9, a process that continues well into adolescence. Once children reach 9–12 years of age, the spine and injury patterns begin to more closely resemble that of adults [19, 20].

Injury Patterns

Cervical trauma is associated with increased risk of neurological damage, and up to 43% of patients with cervical injury have been reported to present with neurologic deficits [12, 21]. And because there is potential for progressive injury as patients grow and their spines continue to develop, proper injury identification and long-term follow-up are both paramount [12]. Trauma to the pediatric cervical spine can result in bony, ligamentous, and/or neurovascular injuries. The Subaxial Injury and Classification (SLIC) System grades both the severity of neck injuries and guides management of injury patterns [22]. Points are allotted based on neurologic status, the morphology of the injury, and the presence of injury to the discoligamentous complex; scores greater than 4 are generally considered sufficient to warrant operative intervention. However, unlike the similarly designed Thoracolumbar Injury Classification and Severity Score (TLICS), the SLIC score was designed to assess CSI in adult patients and has yet to be validated in the pediatric population [23]. Nevertheless, the SLIC score can provide a useful foundation for evaluating CSI.

Fracture Patterns

Subaxial fractures can be morphologically classified as compression, burst, distraction, or translation. Compression fractures, which result when the anterior column fails (wedge deformity) without involvement of middle and posterior columns, are commonly caused by mild flexion with axial loading. As the middle and posterior columns are usually uninvolved, compression fractures generally do not result in neurological deficits as the spinal cord is spared and are considered stable. Burst fractures, generally caused by significant axial loading/compression, are a specific type of compression fracture that occurs when the cervical vertebral body's anterior and posterior walls collapse. Burst fractures are considered unstable and may be complicated by vertebral fragment retropulsion into the spinal canal, potentially causing ligamentous injury and neurological deficits. Distraction fractures result in failure of the anterior or posterior tension bands in the vertical axis; if there is any horizontal or rotational displacement of one vertebra relative to another in any plane, it is termed a translational injury. The AO Spine subaxial cervical spine system allows for accurate, reproducible description of such injuries: compression/burst fractures are grouped into "Type A"; distraction fractures are classified as "Type B"; and translational fractures are listed as "Type C." The classification system allows for further subclassification based on type and extent of injury as well as structures involved.

While fractures can occur at any point along the cervical spine, the upper segments (C0–C3) are most vulnerable to injury in the immature pediatric spine. Fractures of the occipital condyle (OCF) are rare but have been increasingly diagnosed with widespread use of computed tomography (CT) and magnetic resonance imaging (MRI) [24]. OCFs are subcategorized according to the Anderson classification system [25, 26]. Type I OCFs are an impacted comminuted fracture caused primarily by axial forces. Type II OCFs are a displaced fracture of the skull base extending to and involving the occipital condyle, usually caused by a direct blow to the head. Type II OCFs can present with or without ligamentous instability, classified as type IIA and type IIB, respectively. Type I and IIA injuries are considered stable given the absence of ligamentous injury. Type III fractures are an ipsilateral avulsion fracture of the occipital condyle that is mobile and can be displaced into the foramen magnum. These fractures are unstable, and usually caused by a combined force of lateral inclination plus rotation. Of note, patients with OCFs can present with various abnormalities or deficits ranging from pain to limited range of motion, impaired consciousness, and/or fatal atlanto-occipital dislocation (AOD) [27]. In a small study of 14 cases of pediatric OCFs, Momjian et al. [27] showed that approximately half of patients suffered additional injuries to the cranial nerves, brainstem, or high cervical cord. Because OCF injuries do not correlate particularly well with neurologic function, physical signs alone are unreliable in diagnosing OCF [19]. Thus, early diagnosis by inclusion of C0–C2 during CT evaluation is critical, as displaced fracture fragments can potentially lead to delayed injury of cranial nerves or death by brainstem compression [24, 27].

While rare, C1/Atlas fractures, also referred to as Jefferson fractures, in children consistently present with neck pain, neck spasm, decreased range of motion, and head tilt. These injuries result from an axial compression load, with force transmission through the occiput to the subaxial cervical spine via the lateral masses of C1 [28, 29]. Such a force can occur from a fall onto the vertex of the head or being struck by a high-speed motor vehicle. Separation of the C1 lateral masses results in atlantoaxial instability, as the transverse atlantal and alar ligaments are at risk for rupture or avulsion [28].

Rarely, the C2 dens may be fractured in pediatric CSI. Under the Anderson classification system, type I fractures occur along the upper portion of the odontoid peg, above the transverse segment of the cruciform ligament. Type II fractures occur below the transverse portion of the cruciform ligament at the base of the odontoid, and while stable, are at high risk of non-union. Type III fractures occur through the C2 vertebral body and are generally well-tolerated. Hangman's fractures, otherwise known as traumatic spondylolisthesis of C2, results from hyperextension and axial loading. These fractures are notable for fractures through the bilateral pars interarticularis while sparing the odontoid [30]. Under the Levine and Edwards classification system, a type I fracture involves C2 body displacement <3 mm with no angulation, type II fracture involves anterolisthesis >3 mm with a C2-3 angulation <10^0, type IIa fracture involves minimal anterolisthesis but with disruption of the C2-3 disc and >10^0 angulation, and type III fracture involves fixed displacement with an intact anterior longitudinal ligament and fracture of the C2 body posterior wall as opposed to the neural arch [31].

Ligamentous Injury

Pediatric CSI can lead to injuries of the transverse ligament, distraction of the craniocervical junction, atlantoaxial rotatory subluxation (AARS), and AOD. A case illustration is shown in Figure 1. Injuries of the transverse ligament are concerning for increasing the risk of C1/C2 dislocation. Craniocervical junction injuries have a wide range of severity with respect to their presentation; younger children are at higher risk for these injuries, which typically result from medium- to high-velocity impacts [32]. Evidence of craniocervical instability can be detected on imaging by accounting for the following parameters: (a) the lateral atlanto-dental interval (ADI), which is the distance between the lateral dens and medial aspect of C1 lateral mass, and the atlantoaxial interval, which is the width of the C1-2 lateral mass joint. In children, the upper limit of the lateral ADI on CT imaging is typically less than 8 mm and the atlantoaxial interval is typically less than 4 mm. Greater values may indicate secondary damage to the atlantoaxial ligamentous complex [33] (b) dens-basion interval (DBI). While variable ossification of the proatlas among children 2–6 years old should be accounted for, a DBI of 10 and 12 mm in ossified and non-ossified os groups, respectively, can indicate instability [33], (c) basion-axial interval (BAI) ranging 0–12 mm on XR [34, 35], (d) O-C1 joint interval > 3–5 mm [36, 37], and (e) a change in T2 cord signal or a clearly visualized torn tectorial membrane or transverse ligament on MRI.

AARS occur when the alar ligaments stabilizing C1 and C2 are injured. AARS should be strongly suspected in children with acute torticollis following craniocervical injury, as patients often present with only mild neck pain and, in one described case, transient blindness from stretching of the bilateral vertebral arteries [38].

AOD is the most dangerous of injury patterns and is associated with poor prognosis and high rates of mortality. While children are more vulnerable to AOD due to their proportionally larger head sizes and ligamentous immaturity, children and adolescents have better survival rates compared to adults [39]. However, children often suffer from long-term neurologic complications. The majority of pediatric AOD survivors have significant brain and/or spinal cord injuries [40]. Under the Traynelis classification system, AOD is classified as type I (anterior dislocation), type II (longitudinal dislocation), or type III (posterior dislocation) [41]. Any injury involving the tectorial membrane signifies unstable ligamentous injury, often occurring concurrently with AO joint disruption. Progressive MRI changes will result if such injuries are left untreated [42].

While diagnosis of AOD can be challenging, it may predicted with multiple radiographic criteria, though no single criterion is universally used. Accurate and timely diagnosis is imperative for both treatment and prevention of further injury. Missed diagnosis/failure to diagnose has been identified as the single strongest predictor of mortality in AOD. Below, we describe the major parameters for predicting AOD (Fig. 2).

Condylar-C1 Interval (CCI). The most reliable indicator of AOD is the Occipital Condylar-C1 Interval (CCI). The normal OC1 joint is a narrow space held together tightly by ligaments and invariably widens with AOD [36]. The mean CCI is 1.28 mm for children aged 0–18 years, and the CCI and left-right symmetry do not change significantly with age [36]. CCI is superior as a diagnostic criterion for AOD because it is the only test that directly measures the actual joint involved in AOD and cannot be obscured by post-injury changes in other bony landmarks [37].

Wholey's DBI. This refers to the distance between the apex of the dens and the tip of the basion, measured on either lateral X-ray or sagittal CT scan. A DBI ≥12.5 mm on CT scan is diagnostic of AOD in children [43].

Power's Ratio. This refers to the distance between the basion and midpoint of posterior arch of C1 divided by the distance between the opisthion and midpoint of the anterior arch of C1. While the mean normal Power's

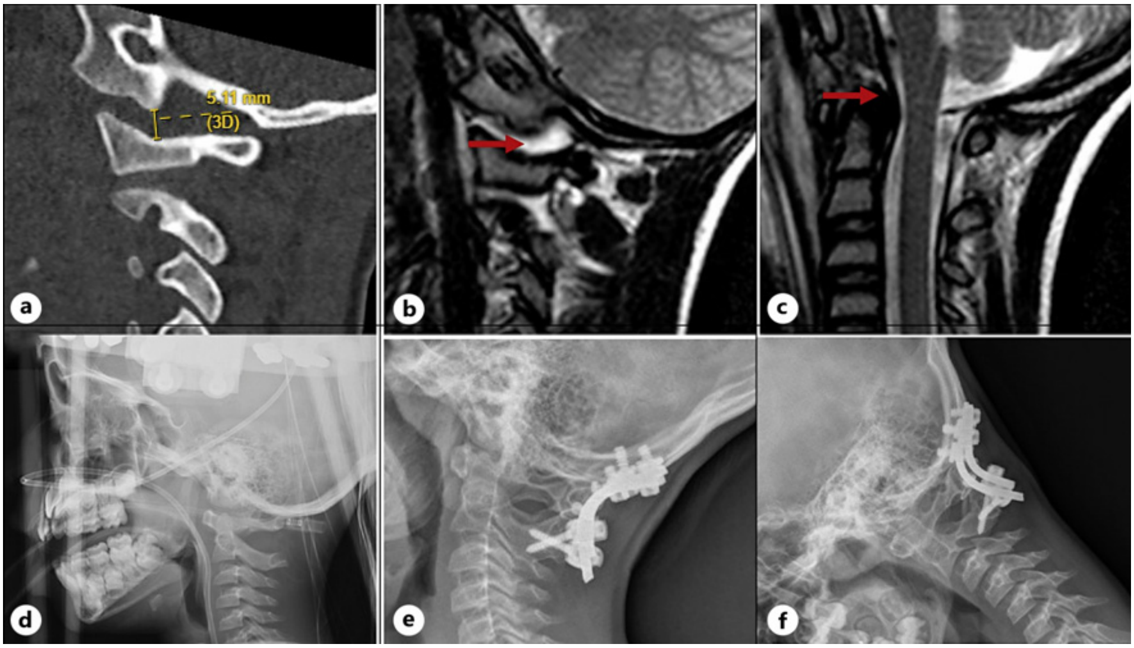

Fig. 1. Management of pediatric AOD. A pediatric patient presented as a restrained passenger in a motor vehicle accident. This patient's examination was notable for neck pain, bilateral abducens nerve palsies, and dysarthria. CT scan of the patient's head and neck was notable for widening greater than 5 mm with anterior translation of the patient's bilateral atlanto-occipital joints (**a**) as well as evidence of capsular rupture on MRI (**b**). MRI also demonstrated prevertebral hematoma from the clivus down to cervical 4 vertebrae and posterior atlantoaxial interspinous ligament widening/edema (**c**). The patient was first placed in a halo brace (**d**). After multidisciplinary discussion, the patient was taken to the operating for posterior spinal fusion from the occiput to cervical 2 utilizing translaminar screws and rib autograft (**e**). The patient was at neurologic baseline postoperatively. The patient was discharged to inpatient acute rehabilitation facility with halo removal 10 weeks post-op. On last follow-up 2 years later, the patient had a non-focal neurological exam with cervical flexion/extension X-rays demonstrating intact cervical spine instrumentation (**f**).

Ratio is 0.77, any Power's Ratio >1 is diagnostic of AOD [44].

Harris' BAI. A line drawn tangentially to the posterior wall of the C2 vertebral body is referred to as the posterior axial line. A second line parallel to the posterior axial line is drawn through the basion. The distance between the posterior axial line and the second parallel line is the BAI. In adults, the normal range for BAI is 12 mm to −4 mm, with the negative value representing the basion falling behind the posterior axial line. In children, the normal range for BAI is 12 mm–0 mm. BAI values that are outside this range are diagnostic of AOD [35]. Harris' BAI had a diagnostic sensitivity of 31% and false-positive rate of 50% [37].

Sun's Interspinous Ratio. This is calculated by dividing the interspinous distance of C1 and C2 by the interspinous distance of C2 and C3, as measured on a lateral X-ray or sagittal CT scan. An C1-2:C2-3 ratio of ≥2.5 is diagnostic of AOD [42]. In a review of 75 cases, Sun et al. [42] report that a C1-2:C2-3 ratio >2.5 on MRI predicted tectorial membrane injuries with 100% specificity.

Comparison of AOD Diagnostic Criteria

Given the importance of accurate diagnosis in AOD, Pang et al. [37] applied the diagnostic criteria discussed above to 26 patient cases (16 with confirmed AOD and 10 without). A CCI threshold of 4 mm or greater predicted AOD with 100% sensitivity and 100% specificity. Wholey's DBI has a diagnostic sensitivity of 50% and false-positive rate of 30%. Power's Ratio had a diagnostic sensitivity of 37.5% and a false-positive rate of 10% [37]. Sun's Interspinous Ratio had a diagnostic sensitivity of 25% and a false-positive rate of 60% [37].

Synchondrosis Injury

The odontoid synchondrosis is highly vulnerable to translational forces [20]. Fractures of the synchondrosis usually result from high-impact trauma (e.g., fall from height, MVA) but non-accidental trauma should be considered in infants [45, 46]. Fractures may affect either the dentocentral or neurocentral synchondrosis. The dentocentral synchondrosis is most often affected in axial injuries among children younger than 7 years old [47].

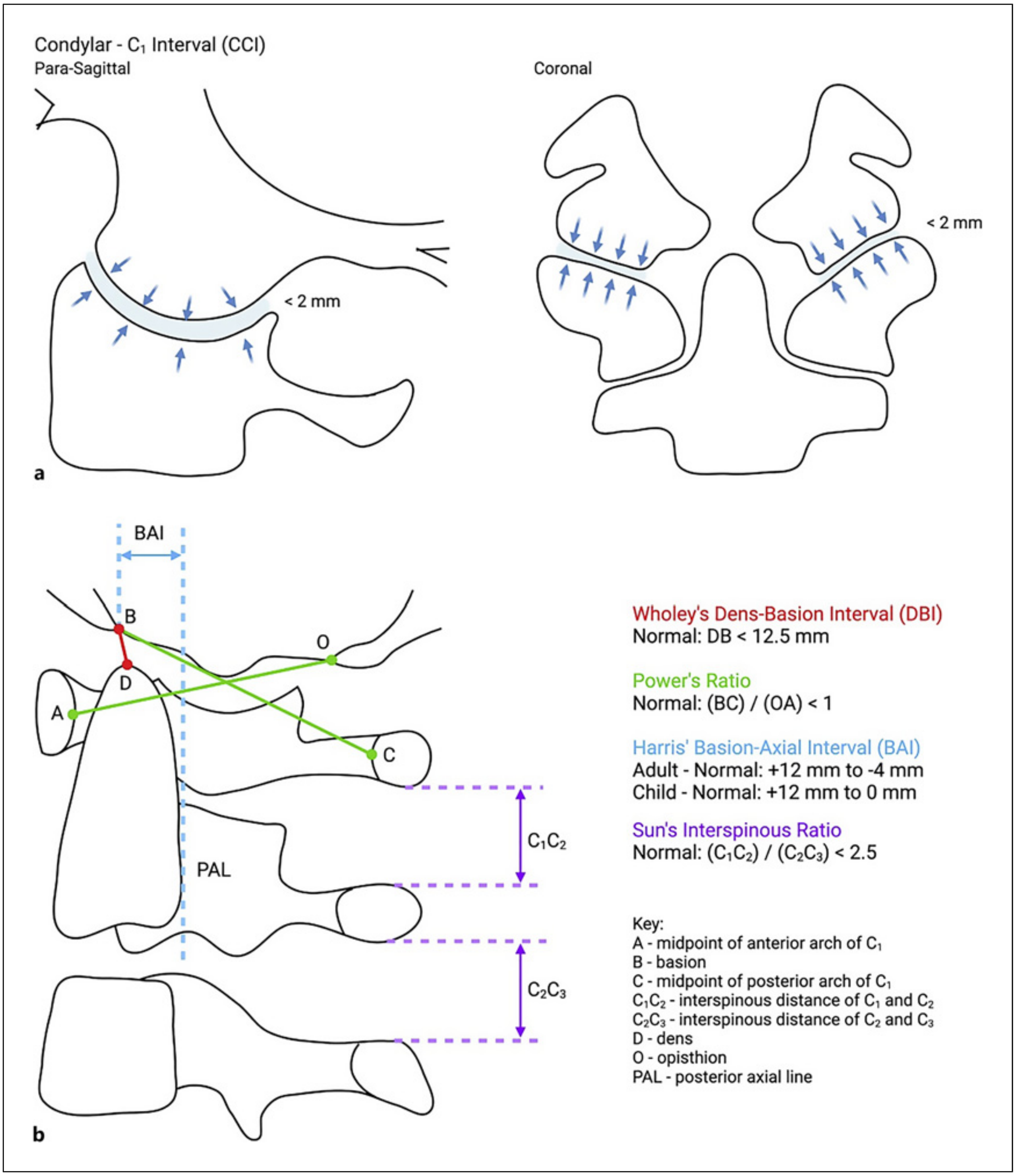

Fig. 2. Atlanto-occipital dislocation (AOD) Parameters. **a** Condylar-C1 Interval (CCI) in the para-sagittal (left) and coronal (right) planes. Normal CCI is less than 2 mm. **b** Major diagnostic criteria for AOD superimposed on a silhouette of the upper cervical spine. A Wholey's Dens-Basion Interval (DBI) shown as the distance between points D and B denoted with the red line. A DBI of ≥12.5 mm on CT scan is diagnostic of AOD in children. Power's Ratio is the distance between the basion (point B) and midpoint of posterior arch of C1 (C1) divided by the distance between the opisthion (point O) and midpoint of anterior arch of C1 (point A) as shown with the green lines. Power's Ratio >1 is diagnostic of AOD. A Harris' Basion-Axial Interval (BAI) is the distance between the posterior axial line (a line tangential to the posterior wall of the C2 vertebral body) and a parallel line drawn through the basion. In children, the normal range for BAI is 12 mm–0 mm, with a BAI on either side of the normal range being diagnostic of AOD. Sun's Interspinous Ratio is calculated by dividing the interspinous distance of C1 and C2 (C1C2) by the interspinous distance of C2 and C3 (C2C3), as measured on a sagittal CT scan or X-ray. An interspinous ratio of ≥2.5 is diagnostic of AOD.

High suspicion for a synchondrosis injury should not delay care, as 26% of patients with such fractures experience persistent neurologic deficits or death [48].

Neurovascular Injury

In blunt cervical trauma, the incidence of cerebrovascular injury (CVI) is approximately 11.5%. The most common cause is high-speed motor vehicle accidents. However, children also engage in a wide variety of activities and play such as trampolines that can lead to hyperextension or flexion of the neck, which can result in CVI [49, 50]. Fractures that extend through the transverse foramen, facet dislocation or jumped facets, and all C1-3 fractures or subluxation increase the risk of CVI [51]. Approximately 57% of CVI involve the vertebral artery, 47% involve the carotid artery, and a small 4% subset involve both [50]. The pattern of injury can lend some clues into which vasculature should be further scrutinized. Carotid artery injuries, for examples, are associated more with skull base fractures while vertebral artery injuries occur more with fractures of the cervical spine [50]. Clinically, carotid injuries tend to fare worse prognostically, as evidenced by longer intensive care stays and higher rates of stroke.

In exceedingly rare cases, pediatric spine trauma can also lead to Horner's syndrome from injury to the sympathetic chain just lateral to the uncovertebral joints. The triad of ptosis, miosis, and anhidrosis should alert the clinician of the likelihood of injury to these nerves [52].

Spinal Cord Injury

The spinal cord can be susceptible to injury because of the flexibility of the pediatric spine. If injured, the neurologic deficits are contingent on which spinal tract(s) were involved, whether the injury was incomplete vs. complete, and the injury level. Although the spinal cord consists of many different gray and white matter tracts, the following are considered to be the most clinically relevant: (1) *corticospinal tract*, which controls ipsilateral motor function, (2) *spinothalamic tract*, which transmits ascending pain/temperature sensation from the contralateral hemibody, and (3) *posterior columns*, which transmit ipsilateral vibratory/proprioceptive sensory information [53]. Injuries to these tracts result in deficits germane to their function: corticospinal injury results in ipsilateral muscle weakness and signs of myelopathy (e.g., spasticity, increased deep tendon reflexes, Babinski sign), spinothalamic injury leads to loss of pain/temperature sensation on the contralateral hemi-body, and posterior column injury leads to ipsilateral loss of proprioception and vibration.

Injury to the spinal cord can be further classified as complete versus incomplete. The widely adopted American Spinal Injury Association (ASIA) categorizes spinal cord injuries as follows: A – complete loss of sensory/motor function below the level of injury, B – complete loss of motor with preservation of sensory function below the level of injury, C – partial loss of motor function below the level of injury, with >50% of muscles having a strength grade lower than 3/5, D – partial loss of motor function below the level of injury with >50% of muscles having a strength grade ≥3/5, and E – normal motor and sensory function [53]. Only ASIA A injuries are considered "complete" injuries. In a small retrospective study of 30 pediatric patients with cervical spine trauma, Katar et al. [12] showed that approximately 35% presented as ASIA C or worse, which reinforces the concept of morbidity associated with CSI. When patients were assessed at 6-month timepoint, fewer than half demonstrated improvement in the neurologic status. Complete spinal injuries to the cervical spine have been associated with mortality rates as high as 50%, as opposed to 16% for incomplete injuries. Comparatively, this 50% mortality rate is 6 times higher than that of injuries to the lower spine [3].

The specific level of injury can also have a significant impact on the patient's clinical outcome. Lesions above C3, for example, can lead to immediate respiratory arrest while lesions at C3-5 can impair diaphragmatic function by way of the phrenic nerve. More distally, cardiac accelerator fibers originate from T1–T4, and thus more proximal injuries may result in an inability to create reflex tachycardia in response to hypotension [51, 54]. The T7 level also controls the adrenal cortical response to stress, and thus cervical injuries can further impair reflex tachycardia [51]. The end product of such injury can be neurogenic shock, which is notable for hypotension and paradoxical bradycardia.

Spinal Cord Neurapraxia

Transient neurologic deficits may be observed in the setting of a sports-related injury, particularly among athletic children playing football [55]. This neurapraxia typically lasts <15 min but up to 48 h post-injury, and children can present with symptoms ranging from focal deficit to quadriparesis [56]. Mechanistically, it is believed that hyperextension, hyperflexion, or axial loading can cause axonal stretch and subsequent micro-vasospasm. Because pediatric spines are more mobile, blunt sports-related impacts can predispose the spinal cord to temporary "bruising" as it shifts within the thecal sac in response to an injury [57]. SCI without radiographic abnormality (SCIWORA) is similarly a transient, self-resolving condition, can be considered synonymous to neurapraxia. Occurring primarily in the setting of higher impact accidents such as motor vehicle accidents, SCIWORA is more commonly seen in children younger than 8 years old as the upper cervical spinal elements shift in response to injury.

Polytrauma

Polytrauma is not an infrequent event, and further compounds the complexity of injury and subsequent management [51]. Proximity to the head means that cervical trauma may occur concurrently with blunt or penetrating head injuries. Alexiades et al. [17] have reported a prevalence ranging from 25 to 50% of concurrent head injuries with cervical trauma cases. And in a 2017 study, Baerg et al. [15] found that children with CSIs also had a higher incidence of retinal hemorrhages, brain infarcts, and hypoxic/ischemic injury. Polytrauma patients in neurogenic shock may also experience significant blood loss, thus presenting with a mixed hemorrhagic/neurogenic shock picture.

Diagnostic Workup

Standard projection radiographs (XR), CT scans, and MRI form the trifecta of diagnostic imaging workup of the spine. Each of these imaging modalities fulfills a unique role and offers different clinical insights into the diagnosis of traumatic injuries. In broad terms, XR is a quick, easily accessible surveillance tool that can detect overall abnormalities in spinal alignment and fracture patterns, CT scans are important for assessing bone quality and for delineating fractures in greater fidelity, and MRI is critical for identifying injuries to the soft tissue, discoligamentous complex, and spinal cord. In children, an individualized, tailored approach is necessary when assessing the risks versus benefits of each imaging modality, as the clinical need for obtaining diagnostic imaging must be balanced with minimizing unnecessary radiation exposure [58].

Cervical X-Ray

Cervical XRs offer a quick and facile method of obtaining baseline spinal imaging in the acute traumatic setting. A single-projection XR is often sufficient to diagnose the majority of CSI [59]. Somppi et al. [60] reviewed 574 children who had undergone cervical XR for trauma, and only found a slightly inferior diagnostic performance compared to CT scans. Overall sensitivity and specificity of XR for detecting CSI was 83% and 97%, respectively. Others have even reported a sensitivity as high as 100% [61]. However, it is evident that there are inherent limitations to relying on cervical XR alone, especially in the context of soft tissue injuries or diagnostically ambivalent cases. Lindholm et al. [59] reviewed over 3,700 cervical XR films in the acute traumatic setting that were followed by either a confirmatory CT or MRI scan. The authors found that all false negatives on XR were secondary to ligamentous injuries, which were subsequently diagnosed on MRI, and that a third of the injuries detected on XR were false positives, which were subsequently ruled out on CT scans. Nevertheless, although CTs and MRI overall offer better diagnostic performance, XR serves an important role as a first-line screening tool for CSI.

Cervical CT Scans

Most bony and ligamentous injuries are visible on CT [15, 62], and CT scans are more specific and sensitive than XR for visualizing cervical spine anatomy [59, 61]. When compared head-to-head, CT scans are often considered superior to radiographs for diagnosing any CSI [63]. Nevertheless, radiation dose and exposure has been one of the longstanding concerns with obtaining routine CT scans following traumatic injuries [64]. In children, the standard radiation dose from a routine head CT scan ranges between 50 and 60 mGy. According to one study conducted in children under 15 years of age, undergoing 2–3 head CTs tripled the risk of brain tumors and undergoing 5–10 head CTs tripled the risk of leukemia. In context, this translates to an absolute excess risk of approximately 1 excess case of leukemia and brain tumor each year per 10,000 children [64]. Furthermore, other studies have shown that CT scans confer up to 25% higher relative risk of developing thyroid cancer [65–67]. As such, the clinical decision to obtain a CT scan should be weighed based on the mechanism of injury and patient's clinical status.

MRI Scan

MRI scans offer the greatest amount of diagnostic information, particularly with respect to evaluating the spinal cord, disc spaces, and ligaments of the cervical spine. In a single-center retrospective review of pediatric trauma patients who underwent both CT and MRI to diagnose CSI, Derderian et al. [67] found that MRI was able to detect subtle, stable injuries in almost half of the patients who had benign CT scans. However, when assessing for unstable injuries, MRI did not confer additional diagnostic utility; in other words, a negative CT scan alone may be sufficient to rule out clinically significant CSI. Nevertheless, one of the primary advantages of MRI is its ability to rule out spinal cord injury, as up to 50% of children with CSI can show no radiologic abnormalities on either XR or CT [3]. Especially in children younger than 8 years old, stretching of the spinal can lead to spinal cord injury without radiographic abnormality (SCIWORA), a transient, self-resolving condition in which the upper cervical spinal elements shift rather than break. An MRI is critical in such situations to ensure that true spinal cord injury is absent, which consequently affects patient management. It is also worth noting that apart from injuries to the spinal cord, other clinically significant injuries – such as vertebral artery shear injuries or epidural hematomas – are much more likely to be diagnosed with an MRI [15]. Importantly, use of fast-sequence spine MRIs have been described in pediatric patients, although they were primarily used to diagnose nontraumatic spinal anomalies or pediatric head injuries [68, 69]. As use of these rapid MRIs become more in vogue, they may become the gold standard for diagnosis and evaluation of CSIs.

Decision-Making in Imaging

One of the primary questions when children present to the emergency room with traumatic injury is whether imaging should be obtained of the cervical spine and, if so, which type(s). In the early 2000s, the National Emergency X-Radiography Utilization Study (NEXUS) and the Canadian C-spine rules (CCR) independently released guidelines to help address this exact problem (Fig. 3). The NEXUS validated criteria are comprised of five clinical findings: (1) presence of neurologic deficits, (2) midline tenderness, (3) altered mentation or loss of consciousness, (4) intoxication precluding accurate examination, and (5) distraction injuries [69]. If none of these criteria are met, the risk of overlooking an injury is negligible; in contrast, a single point on the NEXUS criteria correlates with 1% of those children possessing a true CSI, necessitating XR imaging of the spine [70]. In contrast, the CCR divides patients into subgroups by risk category and their physical exam, with greater emphasis placed on the mechanism of injury. Patients are categorized as “high-risk” if they are elderly (>65 years old), if the mechanism of injury was considered significant (fall from >3 feet, axial load to head, bicycle collision, high-speed motor vehicle accident, motorized recreational vehicles), or if they present with paresthesias in their extremities. All “high-risk” patients are recommended to undergo XR imaging of the spine. Patients are categorized as “low-risk” if they are able to sit or ambulate, deny midline cervical tenderness or neck pain, or the mechanism of injury was a simple rear-end motor vehicle accident. Such patients do not require imaging unless they are unable to rotate their neck by 45° [71].

The decision whether to adhere to the NEXUS or the CCR guidelines appears to largely be institution-dependent. There remains debate over which criteria are better suited in clinical practice. When comparing the two guidelines, Stiell et al. [72] found that CCR had superior specificity and sensitivity, and thus advocate for its use in order to reduce the rates of unnecessary of imaging. In contrast, Ghelichkhani and colleagues [73] reported that the NEXUS was more specific but less sensitive.

However, there is significant concern that neither guideline may be optimized for the pediatric population, as both were constructed on data from trauma patients of all ages. In a retrospective study by Garton et al. [74], the authors found that in children older than 8 years of age, the NEXUS criteria did not miss a single injury among 157 patients. In children younger than 8 years of age, however, two injuries were missed. Similarly, Ehrlich et al. [75] found that both the NEXUS and CCR criteria were not specific or sensitive enough when diagnosing CSI in children 10 years and younger. And in a more recent meta-analysis, Slaar et al. [76] compared the diagnostic accuracy of NEXUS against the CCR, looking at three separate cohort studies with a total of 3,380 patients, 96 of whom had CSI. The overall specificity and sensitivity of NEXUS ranged from 0.2–0.54 and 0.57–1.00, respectively. The CCR guidelines had a specificity of 0.15 and sensitivity of 0.86. Overall, these results suggest that more studies are needed with specific emphasis on pediatric patients to better characterize the validity of existing criteria for obtaining diagnostic imaging.

Furthermore, there is considerable lack of standardization between institutions regarding imaging protocols [77]. In an attempt to address some of these shortcomings, the Pediatric Cervical Spine Clearance Working Group recently proposed a revised consensus-based guideline and algorithm. Patients are first divided into three cohorts by GCS (14/15 vs. 9–13 vs. ≤ 8). Among patients with GCS 14/15, plain radiographs are recommended if there is any report of neck pain, abnormal head posture, or limited neck mobility. If any of these factors are independently corroborated on physical exam, imaging is also warranted. Among patients with GCS 9–13, if there is clinical evidence that the patient will spontaneously recover in mental status, a plain radiograph is recommended and the C-spine is cleared only if the imaging is normal and the patient’s exam improves

Fig. 3. Summary of protocols for cervical spine imaging (**a**) national emergency X-Radiography utilization group (NEXUS) criteria. **b** Canadian C-spine rule (CCR) criteria. **c** Pediatric cervical spine clearance Working group (PCSCWG) criteria.

within 12 h. If a patient with GCS 9–13 does not look likely to improve in mental status or if a patient presents with GCS ≤8, a CT scan is automatically triggered. Even if the CT shows no evidence of injury, the patient's clinical course is closely scrutinized, and if they look likely to improve to GCS 14/15 within 3 days, a clinical exam is repeated and C-spine cleared if the exam is normal. If no improvement is likely, an MRI is performed within that 3-

day time period (Fig. 3) [78]. When the authors of the protocol looked at their pre versus post-protocol cohorts, they noticed marked reductions in plain radiographs (70% vs. 55%, $p = 0.005$) and CT scans (14.5% vs. 5.4%, $p = 0.013$) after protocol implementation. An additional benefit from implementing this focused protocol was the reduction in yearly imaging costs by almost USD 400,000 [78].

Neither the NEXUS nor the CCR criteria specify if or when CT or MRI imaging should be obtained. However, there is some guidance in the literature. Borrowing heavily from the foundations set forth in the NEXUS study, the American Academy of Neurological Surgeons and the Congress of Neurological Surgeons subsequently published a joint guideline in 2013 recommending high-resolution CT scans to determine the condyle-C1 interval in suspected AOD (level I evidence), to further evaluate patients exhibiting at least one NEXUS criteria (level II evidence), to classify suspected atlantoaxial rotatory fixation (level II evidence), or exclude occult fractures and to evaluate suspected areas of injury not adequately visualized on XR (Level III evidence) [79]. Based on the results of the CT scan, the patient may then be referred for additional imaging, neurosurgical consultation, or both to initiate management and treatment of the appropriate underlying injury [80].

There is also a trend toward over-usage of CTs for fear of the consequences of missing an injury. A recent study by Ten Brinke et al. [8] examined the use of CTs for pediatric cervical spine clearance. Although the study was conducted in a Level 2 trauma center, the NEXUS protocol was established as the template, approximately 50% of patients who did not meet NEXUS criteria underwent CT scan as the initial scan at time of presentation. A recent study on the use of CT scans in pediatric trauma showed a false-positive rate of one for every 2 clinically significant imaging findings in the cervical spine. Furthermore, routine CT scans did not translate to more rapid discharges [81] and were associated with worse quality-adjusted lift years and increased cost compared to a more focused, risk-based approach for obtaining CT scans [82]. As such, the risks versus benefits of imaging should be carefully balanced in each individual. Some groups such as Kavuri et al. [83] have advocated instead for early consults to the neurosurgical or orthopedic spine services in the setting of an abnormal plain radiograph or unreliable physical exam. Although the time to collar removal did increase, CT scan use dramatically dropped from 90% to 30% without increasing hospital stay or misdiagnosing CSI.

Although many potential CSIs can be diagnosed on CT, an MRI should be considered if there are signs of SCI, if the child is intubated, or if the child has significant altered mental status (GCS <8). Even in non-intubated patients, imaging can be successfully obtained with either a sedative or analgesic [84]. If SCI is suspected, such as in the case of loss of motor and/or sensory function, MRI is the only imaging modality adequate enough to visualize soft tissue. With respect to children with impaired airways, even healthy children are typically intubated when undergoing an MRI, so in an intubated child who will be unable to participate in a full neurologic exam, an MRI can be performed for efficiency. Similarly, altered mentation will significantly impair conducting a thorough exam and may mask underlying deficits, and thus a full MRI should be performed to survey potential injuries [85]. Thus, in cases of suspected SCI with negative CT scans, the patient should be followed up with an MRI to rule out true SCI. Even in cases with a negative CT, MRI will detect an underlying injury almost half the time, and up to a fifth of "stable" injuries can prove to be unstable with MRI imaging [86].

Management

Triage and Advanced Trauma Life Support

Regardless of trauma severity when a patient first enters into the emergency room, gold standard practice is to assess for and manage the airway, breathing, circulation, disability, and exposure/environmental control per the Advanced Trauma Life Support protocol [87, 88]. A full but expeditious survey is warranted. Early emphasis should be placed on securing the airway, as cervical trauma can impair phrenic nerve and diaphragmatic function, thereby leading to respiratory arrest. Up to 62% of all patients additionally present with polytrauma, particularly thoracic injuries such as pulmonary contusions, pneumothorax, and rib fractures that can further impair respiratory function [89, 90]. Early airway intervention is crucial if upper CSI is suspected. In fact, approximately 18% of blunt trauma patients with proven CSI require emergency intubation within 30 min of arrival in the emergency department [91]. However, significant caution is recommended, as the major challenge is preventing further SCI during the process of intubation, which frequently requires hyperextension of the neck to facilitate visualization of the glottis during direct laryngoscopy [92]. Fiberoptic intubation can improve visualization and minimize cervical motion [51].

In addition, SCI is associated with risk of unstable hemodynamics. As mentioned previously, patients with CSI are at high risk of neurogenic shock as well as hemorrhagic shock from other internal injuries. Great care must be given to any polytrauma patient presenting with hypotension, as both hypotension and hypoxia can increase the risk of secondary injury to the spinal cord. Vasopressors and colloids should be given to maintain mean arterial pressures >85 mm Hg and $PaO_2 > 60$ mm Hg in order to assist with spinal cord perfusion [51].

When children present with polytrauma, CSIs can be more difficult to identify and diagnose [93]. Nevertheless, the initial workup and evaluation triage remains the same. When a child presents to the emergency department with suspected cervical spine trauma, they are fitted with a cervical collar in order to stabilize the spine in case of injury. Immediate immobilization of the spine is critical to prevent further injury [17]. The goal is to maintain the neck in a neutral position. Infants and children younger than 8 years old have heads that are relatively larger than their torsos, and thus require special boards with either thoracic elevation or an occipital depression to maintain the neck in neutral position. Appropriate sizing of the cervical collars is also paramount, as the incorrect cervical collar is tantamount to having no collar [17, 94]. In younger children who may be uncooperative or restless, a rigid collar alone still allows for $>15^0$ of flexion and extension [95]. Thus, supplementing with devices that enclose the head (e.g., Kendrick Extrication Device®) and tape can further supplement immobilization of the pediatric cervical spine [95]. Especially in children with AOD, a cervical collar may induce supraphysiologic distraction and worsen neurologic injury [96].

Once the patient has been stabilized enough on primary survey, they can undergo further workup in suspected CSI as appropriate. Furthermore, “asymptomatic” neck injuries are rare, as the patient will either complain of neck pain or tenderness or the patient will be nonverbal if they have suffered from a moderate to severe traumatic brain injury. When patients are dichotomized as high-risk (i.e., children complaining of neck tenderness or nonverbal) versus low-risk (i.e., no reported neck discomfort) as such, CSI is found in 7.5% and 0% of patients, respectively [97].

Cervical Collar Clearance

In order to determine if the collar can be safely removed, the patient’s clinical exam, mechanism of injury, and imaging findings are collectively taken into account. There is widespread heterogeneity in terms of which services are responsible for clearance at pediatric trauma centers, including general/trauma surgery, neurological surgery, orthopedic surgery, and emergency medicine. In children who are actively moving and participatory, with stable vital signs but without complaint of neck pain or neurologic deficits, the collar can be removed without imaging or with a surveillance X-ray [97, 98]. However, for patients who either do not meet these criteria or for whom the mechanism of injury involves a motor vehicle collision, fall from height>10 feet, or non-accidental trauma, imaging is required to evaluate the extent of injuries [99, 100]. The Pediatric Cervical Spine Clearance Working Group additionally recommends that children presenting with a Glasgow Coma Scale (GCS) ≤ or children with sustained GCS of 9–13 with persistently altered mentation should undergo CT scans [101].

External Orthosis

Many CSI patients do not require surgical intervention, and the vast majority are managed with supportive care, external orthoses, and serial imaging [17]. The most effective external orthoses are the halo devices or Minerva jackets, albeit each comes with its own set of risks [79]. Halo immobilization is often associated with higher complication rates in children than in adults, likely due to a combination of factors including differences in skull thickness, tensile strength of the skin, and smaller body size [102]. However, these complications, which most often include pin site infections or pin loosening, are considered acceptable risks given their potential to correct the injury as well as prevent the need for more significant operative intervention [103–105]. The thermoplastic Minerva orthosis has been offered as a reliable and effective alternative to the Halo device, as it is less of a burden on performing standard activities of daily living and with only one reported complication of skin breakdown [106]. Skaggs et al. [107] found that the Minerva jacket successfully immobilized the cervical spine for a variety of indications including reduction of C1-C2 rotatory subluxation, fusion immobilization, and sternocleidomastoid muscle release for torticollis. Those authors reported only one complication of a dislodged anterior graft that was subsequently managed conservatively. However, given that the majority of pediatric CSI occurs between the occiput and C2, the Minerva may provide less utility in the majority of pediatric cervical trauma [108].

Current guideline recommendations by the neurosurgical AANS/CNS Joint Guidelines Committee recommend closed reduction in the following cases: C2 synchondrosis injury in children less than 7 years old, patients with acute AARS (<4 weeks old) that cannot spontaneously reduce or with chronic AARS (>4 weeks) [79].

In 2021, a multidisciplinary group of pediatric spine experts conducted a modified Delphi study to establish guidelines for cervical spine traction. Their consensus outlined that the primary objectives of cervical traction are to correct sagittal and reducible deformities, resolve dislocations, and streamline surgical approaches, whether anterior or posterior. The experts concluded that traction is appropriate for cases with kyphotic deformities exceeding 31°, basilar invagination, and swan neck deformities. They also agreed that in the absence of neurological symptoms, traction is warranted for unilateral or bilateral jumped facets. However, they cautioned against using traction for AODs and traumatic distraction injuries. They specified that halo traction is unsuitable for children under 1 year old and Gardner-Wells traction is inadvisable for patients with osteogenesis imperfecta and open fontanelles.

Steroid Use

Administration of high-dose corticosteroids in the acute spinal trauma setting has been a highly controversial topic, both within the pediatric and adult populations. In adults presenting with SCI, steroid use is definitively not recommended as it provides minimal benefits while carrying risk such as pneumonia or hyperglycemia [109]. Evidence has largely pointed toward similar conclusions for children. Caruso et al. [110] treated 36 pediatric patients at a Level I trauma center with methylprednisolone. All cases were notable for a concern of acute SCI. Treatment complication rates were high. Regardless of whether the patients had true SCI or not, steroid administration was consistently associated with significantly higher complication rates compared to patients who did not receive steroids. Thus, steroid administration is generally not recommended in the setting of pediatric CSI.

Surgical Intervention

Surgical intervention is warranted in select situations, including the following: unstable injuries, evidence of dislocation with focal deformity, spinal cord compression, and progressive neurologic deficits [79]. Furthermore, surgery is indicated for primary ligamentous injuries of the cervical spine. Although such injuries can heal with external immobilization alone, nonsurgical management often leads to a high rate of persistent or progressive deformity [79].

Fractures

Under conservative management, patients with OCF typically show good functional recovery, including good osseous consolidation with no pain or limited mobility. Stable type I and IIA OCFs are managed with hard collars or cervicothoracic braces, while unstable type IIB and type III fractures should be managed with a halo vest [24]. In a small case series of 15 OCF patients, patients improved with 8 weeks of conservative treatment, and no patients warranted surgical intervention [27].

Children with Jefferson's or C1/atlas fractures should be treated with a rigid brace, which may range from a firm cervical collar to 3 weeks of traction followed by 2 months in a cervicothoracic brace [111–113]. Most reported patients in the literature survive with full recovery, and surgery is rarely indicated.

Management for dens fractures are guided by the Anderson classification. For type I and III fractures, or type II fractures requiring closed reduction, external orthosis is the ideal treatment of choice [114]. Fusion is indicated for patients with penetrating wounds, deformity, nonunion, or inability to achieve closed reduction [115]. In such cases, surgical fixation offers the benefits of achieving reduction, stabilizing the spine, and potentially earlier mobilization [116]. When placing odontoid screws in children, the insertion angle must be adapted accordingly as guided by imaging, as the posterior dens angulation angle changes with age. In the fetal period, the dens begin with anterior angulation and gradually become more posteriorly angulated as early as 4–6 years old, with acceleration during the growth spurt phase [115]. CT studies show that dens dimensions may allow for two 3.5 mm screws to be inserted as early as 1 year of age [115].

Most patients presenting with Hangman's fractures (90%) recover with immobilization alone. Type I fractures are usually managed with rigid cervical collar. Type II fractures with <5 mm subluxation can be treated with reduction in axial traction plus halo fixation for 6–12 weeks. Fractures >5 mm may require surgery. Type IIa fractures are considered unstable and treated first with halo fixation, while type III fractures are generally managed with surgery [32]. If surgery is indicated, surgical fixation with rigid instrumentation may be performed in children over 10 years old versus sublaminar wiring in younger patients (≥3 years age). Although pedicle screws are more stable, sublaminar wiring is superior in younger children because they avoid the risk of impinging on vertebral arteries or vertebral canal [117].

Ligamentous Injury

Management of pediatric craniocervical junction distraction injuries has not been extensively studied. Appropriate treatment must balance the risk of catastrophic outcomes from instability versus the potential unnecessary surgical intervention that leaves the child with limited mobility. Typically, patients without neurological deficits – with the exception of frank AOD –may be treated conservatively with external immobilization [117].

AARS is a common culprit in neck pain and limited mobility in children, often presenting as torticollis. Acute AARS is fast-resolving in children, with complete recovery and no recurrence either spontaneously or after short bed rest plus a cervical brace [118]. Even in children with delayed presentations (>4 weeks of symptoms), AARS may be successfully reduced using halo traction followed by cervical immobilization in a halo vest or Minerva jacket [109]. Closed reduction and immobilization should be trialed first with a rigid cervical collar, and again with a halo jacket if re-dislocated, before attempting surgery [118]. If persistent instability results in recurrent dislocations, open reduction and internal fixation is performed with dorsal stabilization of C1/C2 [38].

Survival rates for AOD have historically been low that there is not extensive literature on treatment, but prognosis has slowly improved with the advent of passenger airbags and improvement in resuscitation techniques in the field [119, 120]. Early recognition and diagnosis is critical. In children, AOD commonly results from high-velocity motor vehicle collisions, making prevention still the best treatment [119]. Early studies have advocated for surgical treatment, which typically involves early posterior occipitocervical fusion [121, 122]. While supplemental halo immobilization can be considered, this may not always be feasible in a polytrauma patient as halo vests can restrict pulmonary function [120]. However, more recent case studies have shown that AOD can be safely treated initially with halo immobilization, preserving cervical mobility and avoiding iatrogenic risks of operation like vertebral artery dissection [121]. This success in the pediatric population is thought to be attributable to the fact that ligaments in children are still developing and thus have a greater chance of natural recovery compared to adults [123]. More research is thus needed to understand the long-term outcomes of external immobilization versus external immobilization in treatment of pediatric AOD, but evidence of instability despite halo immobilization should absolutely receive surgical intervention [121]. In AOD cases, especially those with neurologic decline, the surgeon must be cognizant for the possibility of obstructive hydrocephalus which may even develop into petropharyngeal pseudomeningocele. Nelson et al. [40] hypothesize that traumatic hydrocephalus in AOD develops due to scarring of basal subarachnoid spaces and fourth ventricle outlets secondary traumatic hematoma/hemorrhage.

Surgical Management

Surgical intervention is indicated in many settings including progressive neurological decline and gross instability. Instrumented fusion ensures that unstable elements are immobilized, reducing risk of damage to spinal cord. Given the immature spines of pediatric patients, care should be taken to limit the number of fused levels, especially in younger patients, as effects of fusion on spinal growth is not well understood.

Occipitocervical Internal Fixation

There are a variety of techniques to achieve fixation in the occipitocervical region given its complexity and unique anatomy. Further as the C1-2 joint facilitates extensive rotation and translation, compared to other vertebral levels, atlantoaxial fusion must be able to withstand such forces. A number of wire-graft techniques that have been described including the Gallie, Brooks, and Dickman-Sonntag methods. The Gallie method provides the least stability in extension and rotation as it consists of bone graft held in place by a single midline sublaminar wire wrapped around C1's arch and C2's spinous process. In children younger than 12, this method may be complicated by the wiring cutting through the midline synchondrosis of C1. Providing greater biomechanical stability than the Gallie method, the Brooks technique consists of two bilateral wires that hold a T-shaped bone graft in place by wrapping around C1's posterior arch and C2's lamina. The Dickman-Sonntag method represents a combination of the two aforementioned techniques; a single midline wire is wrapped around C1's posterior arch and C2's spinous process, securing in place a well-fitted wedge of bone graft that sits between the posterior elements of C1 and C2, preventing rotation and translation as well as providing stability in extension.

Instrumented fusion provides even greater stability than wiring. Unique to children, the calvarium is much thinner than that of adults limiting ability to secure the occipital plate. However, the midline keel or lateral mastoid processes may have sufficient thickness to permit screw purchase. Further, inside-out-screws have been developed to limit concerns of potential intracranial injury from penetrating occipital screws. Screws with larger head diameters have been found to be beneficial as force is distributed over a wider area of the thin calvarium. For C1-2 fixation, the transarticular screw promotes strong construct stability and high rate of successful fusion. Further, fixation with transarticular screws is still possible following removal of C1 and C2 arches, necessary for wire-graft techniques, in cases requiring decompression. Placement of transarticular screws may be technically challenging due to relatively small C2 isthmus and proximity of vertebral arteries; however, complications can be avoided with meticulous preoperative planning and usage of intraoperative fluoroscopy and stereotactic navigation. While it still necessitates intraoperative fluoroscopic guidance, the Goel-Harms construct, circumvents the technical difficulties of C1-2 transarticular fixation, by utilizing rods secured by bilateral lateral mass at C1 and C2 pars screws. In odontoid fractures with intact transverse ligament (Type II), odontoid fixation may be preferred over other forms of C1-2 fixation to preserve C1-2 joint mobility.

Subaxial Spine Fixation

Traditionally, sublaminar wiring, bilaterally wrapping adjacent laminae and securing bone graft, has been used for fixation of the subaxial spine. This technique provides relatively high fusion rates and stability compared to other forms including interspinous and interfacet wiring.

As spine technology and techniques have matured, surgeons may opt for posterior fusion constructs using a combination of lateral mass, pedicle screws, and translaminar screws. In adults, lateral mass screws are generally preferred at C3-6 due to these levels having relatively large lateral masses compared to their pedicles. Further, the trajectory of lateral mass screws compared to pedicle screws in the C3-6 reduces the risk of injury to vertebral arteries and nerve roots. While there are several accepted techniques for placing lateral mass screws, the Roy-Camille technique was the first to be described. The technique calls for screw entrance perpendicular to the bony surface at the midpoint of the lateral mass with a 10° lateral angulation. However, lateral mass screws have not been widely adopted in the treatment of pediatric patients as there is limited research studying their biomechanics, safety, and efficacy in this specific population compared to adults. Promisingly, in recent years several studies have demonstrated the feasibility of placing lateral mass screws with one morphometric analysis of 80 patients finding that all studied patients ≥ 4 would be able to tolerate lateral mass screws of at least 3.5×10 mm. In adult populations, pedicle screws are preferred for C7 fixation given C7's relatively large pedicles compared to lateral masses and should be inserted with 25–40° of medial angulation. Pedicle screws may be used at the lower cervical spine in pediatric patients but are not recommended for the upper cervical spine due to elevated risks of iatrogenic neurovascular injury. Recently, translaminar screws have been studied as an alternative to lateral mass screws in pediatric populations, especially for patients with small lateral masses. Compared to other screw placement techniques, translaminar screws reduce risk of iatrogenic injury to vertebral arteries, and adjacent nerve roots; however, the thecal sac and spinal cord may be injured should the ventral wall of the lamina be breached. Rods are then used to connect the screws and provide stability, and bone graft is used to promote fusion. These constructs provide strong stability and high rates of fusion success; however, care must be taken to ensure that a given patient's spinal anatomy and architecture will be able to withstand stress from the construct and will be able to successfully fuse given the reduced bone size and surface in the pediatric spine.

Conclusion

Although pediatric CSI is rare, such injuries can result in potentially devastating consequences for the pediatric patient. In this review, we discuss the epidemiology, injury patterns, diagnosis, and management of CSI in order to provide the tools and understanding necessary for clinicians to properly assess and treat CSI.

Statement of Ethics

An ethics statement was not required for this study type since no human or animal subjects or materials were used.

Conflict of Interest Statement

All authors declare that they have no conflicts of interest.

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