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Comprehensive review on cervical spine accidents in children

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Abstract
Introduction: Young people are particularly vulnerable to the devastating effects of cervical spine injury. This article aimed to do just that by conducting a literature review.
Conclusions: Diagnosis and treatment of spine injuries need an in-depth understanding of the unique anatomy and biomechanics of the pediatric spine.

Keywords: Children, spinal column, injury anatomy, biomechanics

Introduction

Cervical spine trauma accounts for approximately 1.5% of pediatric trauma admissions [79]. The medical, psycholog- ical, and societal costs of severe pediatric cervical spine trauma can be vastly disproportionate to this small percentage [107, 115-117]. An understanding of the unique anatomical, radiographic, and biomechanical characteristics of the pediatric cervical spine is essential to the appropriate care of these challenging patients. The present paper reviews the literature on this topic.

Epidemiology

Most pediatric cervical spine injuries are a result of blunt trauma [79]. In large series, males out number females from
1.5 to 1.9:1 [14, 34, 54, 79]. Motor vehicle-related accidents, which account for 48–61% of all injuries, are the most common mechanism of injury in children both older and younger than 8 years of age [14, 34, 79]. Of these, injuries to occupants (31-42%) predominate over those to pedestrians (11–16%) and bicycle riders (5–6%) [14, 34, 54, 79].
Falls account for 18% to 30% of cervical spine injuries in the younger age group (<8 years) and 11% in the older age group (>8 years) [34, 79]. Sports injuries are more prevalent in the older group (20–38%) and uncommon in the younger group (3%) [34, 79]. Nonaccidental trauma and penetrating injuries are also found in small numbers of very young children and adolescents, respectively [14, 21].
The largest reported series of pediatric cervical spine injury patients (n =1,098) was gleaned from a 10-year interval of the National Pediatric Trauma Registry and probably represents the best epidemiological data from this patient population [79]. Eighty-three percent of these patients had bony cervical spine injuries. Fractures were more common in all age groups, although dislocations were more prevalent in younger children than older children. Upper cervical spine injuries (C1–4) were almost twice as common as lower cervical injuries (C5–7). Seven percent of the patients had both an upper and lower cervical spine injury. Spinal cord injury occurred in 35% of the pediatric cervical spine injuries. About half of these demonstrated no radiographic evidence of bony injury. Seventy-five percent of spinal cord injuries were incomplete and 25% were complete [79].

Embryology and development

An understanding of the developmental anatomy of the pediatric cervical spine facilitates the interpretation of its imaging and the conceptualization of its biomechanical properties. The vertebral bodies undergo chondrification around the fifth or sixth week of gestation [16]. By the fourth month, ossification centers have appeared in all of the vertebral bodies. Ossification continues through adores- cence. Most vertebrae originate from four primary ossifi- cation centers: one in each hemi-arch and two within the centrum.

The body of each vertebra develops from the fusion of the dorsal and ventral ossification centers within the centrum, an event that occurs by the 24th week of gestation [42].

The atlas

Ossification of the anterior arch of the atlas begins in 33% of children by 3 months and in 81% of children by 1 year of age [118]. Complete ossification of the posterior arch occurs by 3 years of age. The synchondroses between the body and the posterior elements fuse by 7 years of age [36].

The axis

The axis is unique in that there are two additional ossification centers that fuse in the midline to form the odontoid process by the 7th gestational month. The body of C2 fuses to the odontoid between 3 and 6 years of age. The fusion line often is visible until the age of 11 years and is visible throughout life in a third of the population [36]. The secondary ossification center at the apex of the odontoid appears between 6 and 8 years of age and fuses with the dens around 12 years of age [67]. Failure of fusion at this location results in ossiculum terminal, a condition that is usually benign but has been associated with atlantoaxial instability [57].

The C2 posterior arches fuse in the midline by 2 to 3 years and fuse with the body by 3 to 6 years. The inferior epiphyseal ring is a secondary ossification center that appears at the inferior endplate of C2 at puberty and fuses with the body by 25 years of age.

The sub axial cervical spine

The development of the sub axial cervical spine is highly conserved between C3 through C7. Ossification of the centrum is present by the fifth gestational month. The arches fuse in the midline by the second to third year and fuse to the body between the third and the sixth year. Secondary ossification centers develop at the anterior transverse processes, spinous process apices, and superior and inferior epiphyseal rings. The anterior transverse process fuses with the vertebrae by the 6th year. The latter three centers fuse by the 25th year [36].

Imaging characteristics of the pediatric cervical spine

Incomplete ossification and physiologic hypermobility of the pediatric cervical spine contribute to imaging findings that can be confused with pathological conditions. Lateral and anteroposterior (AP) X-rays of the cervical spine are frequently used as a primary screening study. Imaging findings within the realm of normal variants in children include prevertebral soft-tissue thickening, increased altitudinal interval (ADI), overriding C1 anterior arch on the dens, pseudo spread of the C1 lateral masses on C2, pseudo subluxation of C2 on C3 and of C3 on C4, any radiolucent synchondrosis, wedging of sub axial cervical vertebral bodies, and the absence of cervical lordosis.

Prevertebral soft-tissue swelling in adults can indicate adjacent cervical spine injury. In children, a thickened prevertebral shadow on plain radiographs can result from expiration, especially if a child is crying [42]. If repeat X-rays during inspiration are infeasible, computed tomogram-phy (CT) of the region is indicated.

In the adult population the normal ADI is less than 3 mm. On plain radiographs of the pediatric cervical spine, this distance should be less than 5 mm [123]. However, some authors report a more stringent 4 mm [58, 118]. The exaggeration in ADI potentially reflects incomplete ossification of the dens and laxity of the transverse ligament. Overriding of the anterior arch of C1 on the dens during extension also can be mistaken for atlantoaxial instability. This finding is normal in 20% of children younger than 8 years old [18].

C1 lateral mass displacement more than 6.9 mm on open-mouth views is the classic radiographic indicator of transverse ligament disruption in adults [98] although magnetic resonance imaging (MRI) has demonstrated the low sensitivity of this technique [27]. As much as 6 mm of C1 lateral mass displacement is common in children younger than 4 years and may be present until the age of 7 years [59, 103].

Pseudo subluxation of C2 on C3 is present in 22% to 24% of normal pediatric static cervical spine radiographs [2, 18, 92]. Although this finding diminishes with increase- ing age, it has been noted in children as old as 14 years [92]. On dynamic films as many as 46% of normal children under 8 years of age have 3 mm of motion of C2 on C3. On lateral X-rays, 14% of children have pseudo subluxation of C3 on C4 [18]. Pseudo subluxation does not correlate with intubation status, injury severity score, or sex [2, 92]. Full reduction of displacement on extension suggests pseudos'- luxation rather than true instability [42].

Swished proposed a method to differentiate pseudos'-bluxation of C2 on C3 from instability caused by a Hangman's fracture [104]. A line is drawn from the anterior cortex of the posterior arch of C1 to the anterior cortex of the posterior arch of C3. This line typically travels less than 1 mm anterior to the posterior arch of C2. If this distance is more than 2 mm, a disconnection of the anteriorly displaced C2 body from the C2 posterior elements is suggested. Pang and Sun proposed that more than 4.5 mm of horizontal displacement at C2/3 or C3/4 should be considered unstable in children younger than 8 years old [75]. In children older than 8 years, more than 3.5 mm of horizontal displacement at any cervical level reflects instability [119].

On both CT and plain X-rays synchondroses can be mistaken for fracture lines. Conversely, fractures through synchondroses can be misinterpreted as within the realm of normal. The dens-C2 body synchondrosis is well corticated and lies below the level of the superior facets of C2, but it can be mistaken for a type II dens fracture. Fractures through the dens-C2 body synchondrosis may be missed in pediatric patients [93]. This is the most common injury involving the odontoid process in children less than 7 years of age [7, 22, 89]. Similarly, the C1 synchondroses can be misinterpreted as fractures or abnormally separated [51]. Epiphyseal growth plates of vertebral bodies can be mistaken for fractures. They also may be the sites of shearing injuries. A working knowledge of the location and evolution of synchondroses is essential to the accurate interpretation of pediatric spine imaging.

In newborns, cervical vertebral bodies have an ovoid appearance with the vertebral interspaces equivalent to the height of the vertebral bodies. With increasing age, the vertebral bodies assume a more rectangular shape. A wedge appearance of the anterior aspect is a common intermediate stage. In particular, mild C3 wedging can persist until 12 years of age [106].

Loss of cervical lordosis, which can indicate injury in adults, is a normal finding in 14% of children [18].

Biomechanical properties of the developing cervical spine

Compared with the extensive literature on the biomechanics of the adult cervical spine, biomechanical studies of the pediatric cervical spine are rare. It is generally accepted that the pediatric cervical spine demonstrates an age-dependent hypermobility resulting from underdeveloped bony anatomy, ligaments, and musculature. Furthermore, forces applied to a proportionally larger head enable a larger moment arm to act on the underdeveloped spine.

In the 0 to 8-year-old group, large series have demonstrated a tendency toward involvement of the occipitoatlantoaxial complex [14, 21, 34, 54, 79] and pure ligamentous injuries rather than fractures. The craniometrical junction is vulned- able in young children for several reasons: (1) The occipital condyles are smaller. (2) The articulation with the lateral masses of C1 is more planar than cup-like, and it is biased toward the axial plane [35, 119]. (3) The relatively large head size coupled with the upper cervical hypermobility places the fulcrum of flexion in the craniometrical region [36, 119] and (4) the odontoid synchondrosis is susceptible to translational forces.

In children older than 8 years of age, injury patterns approach an adult distribution. With increasing age, the fulcrum moves caudally until it reaches the adult position at C5–7 [119]. In older children, cervical spine injuries below the craniovertebral junction tend to be osseous although pure ligamentous injuries still occur. Subaxial hypermobil- ity arises for several reasons: (1) The facet joints are biased toward the axial plane [110]. (2) The anterior wedging of vertebral bodies permits added flexion. (3) The disk-annulus complex allows greater longitudinal expansion and distraction [52, 119]. (4) In children younger than

10 years old, undeveloped uncinate processes permit greater susceptibility to lateral and rotational forces [119].

(5) Finally, the joint capsules and ligaments are more elastic [14, 36].

Early evaluation and management

Prehospital immobilization

Establishment of an airway, adequate ventilation, and cardiovascular support are cardinal principles in the management of any trauma patient. Apnea, cardiorespira- tory arrest, or severe hypotension can result from injury to the high cervical spinal cord [8]. Immediate in-the-field spinal immobilization of any patient with a suspicious mechanism of injury or with a neurological disability is likely essential to prevent repetitive spinal cord or spinal column injury.

As in adults, the goal of immobilization is to retain the pediatric cervical spine in neutral position. In children less than 8 years old who are immobilized on a spine board, the relatively large head compared with the shoulder girdle and torso places the cervical spine into flexion regardless of the presence of a collar [111]. In one series, more than 20% of children 8 years and older immobilized on a backboard demonstrated more than 10° of cervical flexion (C2–C6 Cobb angle) [24]. Herzenberg *et al*. have recommended the use of an occipital recess or thoracic elevation to eliminate the backboard-induced flexion [48]. Nypaver and Treloar determined that children under 8 years require a mean of cm of thoracic elevation with respect to the occiput to achieve neutral position [65].

In a trauma setting, infants and young children are often uncooperative and restless. Immobilization with a rigid collar alone may allow more than 15° of flexion and extension [50]. A rigid collar combined with supplemental devices that partially enclose the head (e.g., Kendrick Extrication Device®) and tape provide the best prehospital immobilization of the pediatric cervical spine [50]. Cervical collars can lead to supraphysiologic distraction and neuro- logic injury in the presence of occipitoatlantal dislocation [28]. Sandbags and tape should be used in this situation instead.

Clinical clearance of the cervical spine

Clinical clearance of the cervical spine can be undertaken in a subset of pediatric trauma patients. Laham *et al*. [56] established criteria for clinical clearance of the cervical spine in a retrospective series of 268 head-injured pediatric patients. Patients with isolated head injuries who were able to communicate and who had no neck pain or neurological deficits were classified as low risk (*n*=135). High-risk patients (*n* =133) were those less than 2 yearsold, those incapable of verbal communication, and those with neck pain. All patients underwent cervical spine X-rays. No injuries were found in the low-risk group, and ten injuries were found in the high-risk group. Laham *et al*. [56] concluded that cervical spine X-rays are unnecessary in pediatric patients who fulfill the low-risk criteria.

Viccello *et al*. [113] reported 3,065 pediatric patients in a multicenter prospective trial that assessed the utility of cervical spine imaging. Six hundred and three patients met five low-risk criteria, which were defined as the absence of midline cervical tenderness, evidence of intoxication, altered level of alertness or intubation, focal neurological deficits, and painful distracting injury. All patients under- went at least three-view cervical spine imaging. No patient who m*et al*l five low-risk criteria had a cervical spine injury. At our institution, we use the five low-risk criteria studied by Viccellio *et al*. [113] in combination with a sixth criterion, which requires the ability for appropriate verbal communication before the cervical spine can be cleared.

Imaging

All children who do not meet the above low-risk criteria should undergo at least AP and lateral cervical spine radiography with swimmer's views as necessary. Swischuk *et al*. have questioned the utility of open-mouth views in children under 5 years of age [105]. In a series of 51 pediatric patients with cervical spine injuries, Buhs *et al*. concluded that open-mouth views provided no additional information beyond that found on AP and lateral views in children below 9 years of age. Instead, the authors recommended eliminating the open-mouth view and obtain- ing a CT scan in this patient population [15].

The use of CT as a primary tool for cervical spine imaging is controversial. Management guidelines from the American Association of Neurological Surgeons\Congress of Neurological Surgeons [2] suggest that "CT of the cervical spine should be used judiciously to define bony anatomy at specific levels but is not recommended as a means to clear the entire cervical spine in children." In adults, a growing body of literature indicates the signifi- cantly higher sensitivity of CT compared with radiography for the evaluation of cervical spine injuries, especially in obtunded or intubated patients [13, 44, 88, 124]. Similar studies in the pediatric population are lacking. CT-based protocols have replaced plain films in adults who cannot be cleared clinically [87].

Slack and Clancy have advocated CT imaging in obtunded pediatric patients [96]. Although the cervical spine in young children is often easily visualized on plain X-rays, [2] missed fractures on plain films alone have led to neurological injury in this population [6]. Given the potentially devastating clinical consequences of a missed pediatric cervical spine injury, we recommend CT imaging in all patients who do not satisfy the low-risk criteria discussed in the previous section. Furthermore, CT imaging can prove useful in preoperative planning.

MRI is far superior to CT in delineating nonosseous anatomy. Flynn *et al*. examined the use of MRI in the evaluation of pediatric cervical spine injury [38]. By institutional protocol, MRI was obtained if at least one of four criteria was met: (1) an obtunded or nonverbal child with a suspicious mechanism of injury, (2) equivocal plain films, (3) neurologic symptoms without radiographic findings, or (4) an inability to clear the cervical spine based on clinical or radiographic evidence within 3 days of injury. MRI altered the diagnosis based on plain radiography in 34% of cases. Frank *et al*. have reported that the use of MRI is associated with more rapid cervical spine clearance and shorter stays in the intensive care unit in obtunded and intubated pediatric trauma patients [39]. Of 52 pediatric trauma patients with normal plain radiographs and CT scans of the cervical spine, 31% demonstrated changes on MRI [53]. These findings ranged from soft-tissue or ligamentous signal changes to a bulging disk. The MRIs influenced surgical planning in four patients. MRI is useful in the evaluation of spinal cord injury without radiographic abnormality (SCIWORA) [43] although findings may be normal in the pediatric population with this injury [26].

We use MRI whenever a neurological deficit is present and to assess the extent of ligamentous involvement, particularly with craniovertebral junction injuries. We have a low threshold for obtaining MRIs of the cervical spine in obtunded young children with mechanisms of injury that are high risk for injury to the craniovertebral junction. However, MRI is a static test and does not necessarily predict cervical spine instability [49]. The extent of injury demonstrated on MRI can be used to guide management [53].

Flexion-extension films enable the determination of dynamic instability. Several authors have questioned their use in the setting of adequate normal static films. Dwek and Chung [33] reported a series of 247 pediatric trauma patients. No child with normal neutral X-rays demonstrated instability on flexion-extension views. Ralston *et al.* [83] similarly reported 129 pediatric trauma patients and concluded that flexion-extension radiography was unlikely to be abnormal when isolated loss of lordosis or no acute abnormality was evident on AP and lateral cervical spine radiographs. Woods *et al*. concluded that flexion-extension films were not useful in the setting of normal static cervical spine films [125].

Methylprednisolone

There are few data on the use of methylprednisolone specific to pediatric patients. The Second National Acute Spinal Cord Injury Study included 13- to 19-year-old patients, but this demographic group comprised only 15% of the overall study population.

Patterns of pediatric cervical spine injury

Occipitoatlantal and atlantoaxial dislocation

When distraction injuries are considered, the occipitoatlantoaxial complex can be regarded as one unit. The O-C1 and C1–C2 joint capsules and the atlantooccipital and atlantoaxial membranes do not contribute significantly to the vertical stability of the craniocervical junction [23, 123]. The tectorial ligament, alar ligaments, and surrounding musculature appear to have the largest roles in stabilizing this segment [32, 47, 77, 121].

Although occipitoatlantal and atlantoaxial dislocation injuries are uncommon, they are often seen in young children involved in high-speed motor-vehicle accidents, auto versus pedestrian accidents, or in airbag-related injuries [62]. Associated neurological deficits are partial or absent. Complete neurological injury at this level usually results in rapid death. In this patient population, traction and a cervical collar can lead to overdistraction and worsening neurological injury and should be avoided [28].

Diagnosis of occipitoatlantoaxial dislocation requires a high index of suspicion, especially in victims of pedestrian-motor-vehicle accidents and motor-vehicle accidents with or without ejection. Reconstructed coronal and sagittal CT images can demonstrate unilateral or bilateral joint widening at O-C1 and/or C1–2. At C2, widening of the retropharyngeal space beyond 7 mm is a subtle sign of high cervical injury. MRI can define abnormalities of joints, ligaments, and soft tissues at O-C1 and C1–2. Sun *et al*. have emphasized the integrity of the tectorial membrane on MRI as a critical factor in determining both occipitoatlantal and atlantoaxial stability against vertical distraction [102]. Definitive treatment of occipitoatlantoaxial instability requires surgical fusion.

Atlantoaxial rotatory fixation

Atlantoaxial rotatory fixation (AARF) is an alteration of the normal rotational relationship between the atlas and axis. This condition ranges from significant limitation of motion to absolute fixation. Trauma, upper respiratory infections, and head and neck surgery are the main causes for this disorder.

Fielding and Hawkins established a four-tier classifica- tion system [37]. Type I AARF is defined by an intact transverse ligament. Types II and III injuries are defined by the disruption of the transverse ligament alone and by disruption of the transverse and alar ligaments, respectively. These injuries are associated with a progressively widened ADI corresponding to increased displacement of the atlas on C2. Type IV AARF is defined as a posterior rotatory displacement of the atlas on C2. This injury is very rare and can only occur in the setting of a hypoplastic odontoid process. Types II, III, and IV AARF are easily defined on CT and MRI and usually require surgical stabilization of the atlantoaxial complex.

Type I AARF is most difficult to diagnose because the pathological C1–C2 fixation can appear within the range of physiologically normal on static imaging [71]. In this largely pediatric disorder, patients have painful torticollis in the “cock-robin” position with the head turned to one side and the neck laterally flexed in the opposite direction. Ligamentous laxity and shallow C1–C2 lateral mass articulations predispose children to initial overrotation and subluxation [101]. Spasms of the cervical musculature, synovial inflammation, or mechanical obstruction of the

C1–C2 articular surfaces have all been implicated in maintenance of the deformity [101].

Traditionally, dynamic CT is used to evaluate AARF [85]. In this protocol, fine-cut CT imaging is used to image the atlantoaxial span in the presenting position and at the limits of rotation in either direction, as dictated by the patient's discomfort. Limitation or absence of motion is used to diagnose AARF, but the reliability of this technique has been questioned [1, 123].

Pang and Li have refined the conceptualization of Fielding and Hawkins Type I AARF from that of a locked angle of rotation of C1 on C2 to that of a "pathological stickiness" between C1 and C2 that leads to abnormal motion on rotation [71]. In normal individ- uals, axial rotation of the head results in three discrete phases of C1 motion on C2 [71]. From 0° (defined by the head facing straight forward) to 23° of head rotation, C1 rotates independently while C2 remains immobile. From 23° to 65°, C2 rotates with C1, albeit more slowly. At 65° of head rotation, the angle of C1–C2 rotational separation reaches a maximum of 43°. Further head rotation from 65° to 90° is characterized by lock-step motion of C1 with C2 and is entirely provided by subaxial rotational mobility.

Based on an analysis of 40 pediatric patients presenting with torticollis, Pang and Li [72] refined the dynamic CT protocol and classified Fielding and Hawkins Type I AARF into three subtypes corresponding to decreasing amounts of "pathological stickiness." Atlantoaxial scans are obtained in the presenting position, with the nose pointing directly forward and with the head turned to the contralateral side as much as the patient can tolerate. The C1–2 rotational angle is assessed at each position. In subtype I, AARF there is no motion between C1 and C2. In subtype II AARF the C1– C2 rotational angle will decrease but never approach zero despite maximal contralateral neck rotation. In subtype III, AARF the C1–C2 rotational angle will reduce to zero but only with rotation of the head greater than 20° past midline to the contralateral side. A fourth group of patients demonstrated indeterminate pathology between subtype III AARF and normal.

Delays in treatment of AARF lead to worsening C1–C2 adherence. Severity and chronicity of AARF are both independently associated with more difficult and longer treatment, a greater chance of recurrence, higher rates of irreducibility, greater need for surgical stabilization, and higher rates of complete C1–C2 motion segment loss [73]. Chronic subtype I AARF patients should undergo halo ring traction followed by halo vest immobilization for 3 months. Chronic subtype II patients should undergo halter or halo traction followed by halo vest immobilization for 3 months. Subtype III AARF should undergo halter traction followed by immobilization in a cervicothoracic orthosis for 3 months. First recurrences in the orthosis are treated with repeat traction and immobilization. During or after halo vest immobilization, irreducible deformity, or recurrence is treated with surgical fusion of C1–C2.Odontoid injuries

In children under 7 years of age, odontoid injuries are typically avulsions of the synchondrosis between the body of C2 and the dens [7, 22, 61, 89]. Falls and high-speed motor-vehicle accidents, especially with children secured in forward-facing car seats, have been implicated in this injury pattern [66]. Many patients with odontoid synchodrolysis are neurologically intact because a high cervical spinal cord injury is otherwise fatal. Lateral X-rays often show an anteriorly displaced odontoid peg [94]. Reconstructed CT images may show widening of the synchondrosis.

Epiphyseal injuries appear to have a high likelihood of healing with closed reduction and immobilization. Several authors have utilized halo or plaster cast immobilization as first-line treatment with most patients achieving stable fusions [61, 66, 94]. This management strategy preserves the motion segment and avoids surgery in this very young population. C1–2 fusion may be necessary when nonoper-ative treatment fails.

Subaxial ligamentous injuries

Injuries to the subaxial cervical spine have been reported [34, 122] in children under 8 years of age but are generally rare. As the pediatric spine matures toward adult-like biomechanics, subaxial injuries become more common with an increasing proportion of bony rather than ligamen- tous injuries.

The severity of subaxial soft-tissue and ligamentous injuries varies. Mild forms may present with neck pain but no abnormality on CT or dynamic plain films of the cervical spine. More severe injuries may be associated with widening of facet joints, widening or collapse of the disk space, and separation of the spinous process. Short T1-weighted inversion recovery MRI sequences delineate ligamentous, soft-tissue, joint capsule, and epiphyseal endplate injury but may not correlate well with cervical stability [49]. White and Panjabi have suggested that more than 11° of angulation and/or 3.5 mm of subluxation between adjacent vertebrae implies significant ligamentous injury with the likelihood of instability [122]. Based on unpublished data from Pang, Brockmeyer has suggested that more than 7° of kyphotic angulation between adjacent vertebral bodies in the pediatric spine implies unstable ligamentous injury [119]. This poor tolerance for angulation reflects the increased recoil forces within the intact pediatric cervical spine.

Soft-tissue and ligamentous injury without radiographic abnormality on CT or dynamic X-rays is managed with analgesics and a soft collar, as necessary. If neck pain limits sufficient excursion on dynamic films, the patient is placed in a hard cervical collar and re-evaluated with dynamic films after a 2-week interval.

Patients with more substantial soft-tissue and ligamen- tous injury with evidence of widened facet joins, disk spaces, or spinous processes need to be evaluated carefully. Pennecot *et al*. reported that 8 of 11 patients with such injuries managed with reduction and a collar required surgical fusion for instability [80]. MRI may help delineate the extent of injury and influence management. If nonop- erative management is undertaken, we recommend hard- collar immobilization and meticulous long-term follow-up with dynamic X-rays to evaluate for late instability. Any neurological deficits resulting from spinal column instability should be treated with operative stabilization.

Unilateral or bilateral facet dislocation is a relatively common injury pattern of the adolescent pediatric cervical spine. It is caused by a flexion-distraction mechanism and complete disruption of facet capsules. In a patient with bilateral jumped facets and motor-complete spinal cord injury, we use emergent manual reduction followed by immediate MRI to evaluate for an epidural hematoma or herniated disk. In a neurologically intact patient with jumped facet(s), we first obtain an MRI to evaluate for a herniated disk or hematoma within the canal. In the absence of such a lesion, the patient is placed in tongs or halo traction for closed reduction of the deformity. In patients with motor-incomplete spinal cord injury and jumped facet(s), we immediately obtain an MRI to evaluate for disk material or hematoma within the spinal canal. In their absence, manual or weighted traction can be used to reduce the deformity, based on the severity of motor injury. In all cases anterior and/or posterior surgical stabiliza- tion at the level of injury is necessary. Surgery should be undertaken on an emergent basis to treat compressive pathology within the spinal canal.

Spinal cord injury without radiographic abnormality

The syndrome of SCIWORA was described by Pang and Wilberger in 1982 [76]. The incidence of SCIWORA in pediatric patients with spinal cord injury has been estimated between 5% and 67% [70]. A meta-analysis conducted by Pang places this number at about 35% [70]. In younger patients, falls and pedestrian-motor-vehicle accidents are a common cause of SCIWORA. In adolescents, sports injuries and motor-vehicle accidents are more common. In neonates, hyperflexion and hyperextension resulting from child abuse can lead to devastating SCIWORA.

The pathophysiological basis for SCIWORA is the hypermobility of the pediatric cervical spine. When subjected to traumatic hyperflexion, hyperextension, or distraction, the spine recoils to its physiological state while the spinal cord, with little tolerance for deformation, sustains varying amounts of injury [70, 74]. Spinal cord ischemia from vertebral artery injury has also been proposed as an underlying mechanism [124]. Patients present with a spectrum of neurological manifestations ranging from mild transient sensory symptoms to quadri- plegia. Children under 8 years of age are much more likely to have more rostral and severe SCIWORA than older children [30, 124]. In 8- to 16-year olds, SCIWORA tends to occur at lower levels and to be less severe than in younger children [30, 68, 124].

Fundamental to the definition of SCIWORA is the absence of abnormality on static and dynamic flexion/ extension films, CT imaging, and X-ray or CT myelog- raphy. Also excluded are injuries from penetrating trauma, obstetric complications, and electrical shock. MRI enables superior characterization of both the spinal cord and surrounding nonosseous support structures.

Pang reported the high prognostic utility of MRI in 50 SCIWORA patients [70]. At presentation MRI findings within the spinal cord were divided into major hemorrhage, minor hemorrhage, edema, and no-abnormality categories. Patients with major hemorrhage on MRI presented as Frankel grades B and C (severe deficits) and remained at this level of impairment long-term. Patients with minor spinal cord hemorrhage also presented as Frankel grades B and C, but 40% improved to grade D at 6 months. Of patients with edema only, 44% presented as Frankel grades B and C and 56% presented as grade D (minor deficits). At 6 months, 75% percent of patients who had presented with edema only were Frankel grade D and 25% were grade E (normal). There were no MRI findings in 23 patients with clinical SCIWORA. These patients universally made a complete recovery.

MRI is useful in characterizing non-neural injury to the cervical ligamentous and soft tissues in SCIWORA. Injuries to the anterior and posterior longitudinal ligaments, epiphyseal growth plate, facet joints, tectorial membrane, and disk spaces have been documented on MRI [70]. Pang proposed the concept of "occult" instability of the spine in SCIWORA patients, even in the setting of normal dynamic films with sufficient excursion [70]. In occult instability, the ligamentous and soft tissue structures are injured but not destroyed. They are able to withstand moderate physiologic forces but are vulnerable to significant stress. The literature provides scant direct evidence for this concept [30], but occult instability is proposed as a possible cause of the delayed neurological deterioration that has been reported in SCIWORA patients [46, 68, 70]. Occult instability has also been implicated in recurrent SCIWORA [81]. In this entity, a minor trauma after an initial SCIWORA episode causes recurrent symptoms. Ostensibly, the injured spinal cord is more vulnerable to recurrent injury and the weakened non-neural structures may facilitate the recurrence.

In the clinical setting of SCIWORA, MRI can be completely normal [26, 43]. Pang reported that MRI was positive in 64% of pediatric SCIWORA patients with persistent motor deficits lasting more than 24 h, in 27% of patients with deficits lasting fewer than 24 h, and in 6% of patients with only sensory symptoms. He advocates repeating MRI 6 to 9 days after injury because edema may take 3 to 4 h to develop after the initial insult, and small foci of hemorrhage within the spinal cord may not manifest until converted to methemoglobin [81].

Cervical immobilization of patients with SCIWORA is controversial. If dynamic films sufficiently demonstrate stability of the cervical spine, the role of cervical immobilization is unclear [4]. Pang and Pollack advocated 12 weeks of immobilization in a Guilford brace to allow ligamentous injuries to heal and to prevent recurrent SCIWORA [74]. Bosch *et al.* [10] reported that rigid braces, including the Guilford, Aspen, Miami J, and Minerva cast, did not prevent recurrent SCIWORA. They questioned the theory of occult instability as a causative factor. In the setting of only extraneural MRI findings, neurological recovery, and no neck pain, we recommend hard collar immobilization for 2 weeks followed by dynamic films. With neural findings on MRI, 12 weeks of immobilization followed by dynamic films is appropriate.

Cervical cord neurapraxia

Cervical cord neurapraxia, also known as spinal cord concussion or a stinger, likely represents a mild form of SCIWORA that occurs in athletes playing contact sports. Sensory and motor symptoms involving both arms, both legs, or all four extremities can occur [108]. The symptoms usually last 10 to 15 min but can persist as long as 48 h [109]. In adult athletes, cervical cord neurapraxia is often related to cervical stenosis. The relative risk of an athlete sustaining cervical cord neurapraxia a second time increases exponentially compared with the risk of sustain- ing cervical cord neurapraxia the first time [17]. Boockvar *et al*. reported 13 children, aged 7 to 15 years, with cervical cord neurapraxia with no evidence of spinal stenosis [9]. In this population, cervical cord neurapraxia was attributed to cervical hypermobility. Most patients were managed with 2 weeks of cervical immobilization in a hard cervical collar followed by dynamic films. At a mean follow-up of 15 months after injury, all children had returned to sports without restriction with no recurrence of cervical cord neurapraxia or neck pain.

Neonatal injuries

The incidence of birth-related spinal cord injuries is about 1 in 60,000 [114]. The upper cervical spine is the most susceptible to injury [60] and is associated with cephalic presentation and the use of forceps [60, 63]. Infants present with flaccidity and absence of spontaneous motion. Injured infants who do not make respiratory efforts during the first day of life tend to remain ventilator dependent [2, 114]. Spinal immobilization with a thermoplastic molded device spanning from the occiput to the thorax has been used in the management of this difficult problem [2].

Odontoid

Os odontoideum is a well-corticated odontoid process that lacks continuity with the body of C2. Both traumatic and congenital causes of os odontoideum have been documented [25, 112]. Two anatomical subsets of os odontoi- deum exist: orthotopic and dystopic. An orthotopic os moves with C1 whereas a dystopic os is fixed to the basion. Patients can present with occipitocervical pain, myelopathy, or vertebrobasilar ischemia [3]. The natural history of os odontoideum has not been adequately defined, leading to significant controversy about its appropriate management.

The initial diagnosis can easily be made with lateral plain films. Multiple authors have reported that the degree of C1–2 instability on flexion-extension X-rays does not correlate with the presence of myelopathy [95, 99, 120]. However, these authors have also reported that a sagittal diameter of the spinal canal less than or equal to 13 mm on plain X-rays is strongly associated with myelopathy [95, 99].

Spierings and Braakman [99] reported nonoperative management of 16 patients with os odontoideum without myelopathy. At a median follow-up of 7 years, no patient had suffered neurological deterioration. As an option, the Guidelines for the Management of Acute Cervical Spine and Spinal Cord Injuries suggest that patients without neurological deficits, but with instability at C1–C2 on flexion-extension studies, can be managed without operative intervention [3]. Given the potential for neurological injury in children with os odontoideum resulting from minor trauma [20], Brockmeyer believes that the risks of untreated os odontoideum outweigh the risks of C1–2 fusion [11].

Operative and nonoperative management considerations

Many pediatric cervical spine injuries can be treated with halo or hard collar immobilization [45, 69]. Indications for surgical intervention include an unstable injury, irreducible fracture, or dislocation, progressive neurological deficit from compression, and progressive deformity [12, 34, 45]. Within the last decade, the percentage of pediatric cervical spine trauma patients managed surgically has increased due to advances in fixation systems and techniques [12, 34]. Surgical stabilization of the spine, combined with early mobilization of pediatric patients with a spinal cord injury, likely reduces the risk of deep venous thrombosis, decubitus ulcers, and respiratory infections [12, 41].

Historically, pediatric cervical spinal fusion was limited to posterior bone and wire techniques followed by halo or cervicothoracic immobilization. These techniques have a higher rate of failed fusion than contemporary rigid fixation techniques [12, 86, 97]. However, the smaller anatomy and greater proportion of cartilage in the young pediatric spine demand great accuracy in the placement of any screw. Additional concerns in pediatric spine fusion are the development of adjacent level disease and the “crankshaft” phenomenon characterized by continued growth of bone at fixated levels, resulting in a deformity.

Occipitocervical surgical stabilization

Occipitocervical fusion with threaded contoured rods and wiring has proved effective in stabilizing the adult craniocervical junction [5]. Schultz *et al*. advocated this technique in children older than 12 months, suggesting that the rigidity afforded by this method may eliminate the need for a halo [90]. We have used this technique in children as young as 11 months with success [84]. Several authors have also used C1–C2 transarticular screws or C2 pedicle screws coupled with rigid loops and plate or rod constructs in pediatric patients with excellent success [11, 41, 69]. We have also utilized keel screws coupled with C1 lateral mass screws and C2 pars screws for occipitoatlantoaxial stabilization in young pediatric patients.

Atlantoaxial surgical stabilization

Traditionally, atlantoaxial fusion in the pediatric population was accomplished by posterior wiring using Sonntag and Gallie-type constructs [29, 78]. Gluf and Brockmeyer [41] reported 67 pediatric patients who underwent C1–C2 transarticular screw fixation. Of these 67 patients, 65 developed successful fusion without application of a halo. Two unilateral vertebral artery injuries occurred without permanent neurological deficit. There were four infections and one hardware failure attributed to a novel fixation device. The authors successfully placed transarticular screws in 13 patients younger than 4 years old, the youngest being 18 months old. Brockmeyer emphasized the importance of obtaining preoperative multiplanar reconstructions of thin-cut CT scans to determine the appropriate screw size, its entry point, and its trajectory [11]. In a series of more than 50 patients who underwent C1–C2 transarticular fixation, growth was arrested at the fused atlantoaxial level and no craniovertebral deformities developed [11].

Subaxial surgical stabilization

Increasingly, anterior and posterior subaxial instrumentation and techniques are used for pediatric applications. To date there has been little rigorous examination of the use of these techniques in children. Short stature and low-profile anterior plating systems have been placed in children as young as 3 years old [11]. Small vertebral bodies and cartilaginous endplates provide little margin for error when placing anterior screws in young children [11]. Shacked *et al*. successfully used the anterior cervical approach for autograft arthrodesis of cervical segments in six pediatric trauma patients [91]. No instrumentation was placed, but the patients underwent postoperative rigid immobilization in a halo or Minerva cast. Posterior instrumentation is also limited by the constraints of small anatomy. Brockmeyer reported that pedicle or lateral mass screws can be placed in children as young as 4 years old [11]. In very young patients, posterior bone and wiring techniques followed by immobilization may still represent the best treatment option.

Bone grafts

Autograft has been shown to be superior to allograft for use in posterior cervical fusion constructs [55, 100]. Much of this work predates the current era of rigid internal fixation. Composite bone grafts, consisting of demineralized bone matrix and aspirated bone marrow, may reduce morbidity and still maintain the rates of fusion associated with iliac crest autograft [82]. Options for autograft harvest in pediatric patients include the iliac crest, rib, and split- and full-thickness calvarial grafts. In young children, iliac crest harvest may not provide sufficient bone. Both iliac crest and rib harvest can cause severe postoperative pain, the latter potentially resulting in postoperative splinting. Chadduck and Boop have advocated rostral extension of the posterior midline cervical incision and harvest of parietal bone [19]. The lambdoid suture may not be ossified and should not be incorporated in the graft.

Traction and immobilization devices

The use of traction in young children has not been well studied [2]. The thin calvaria in this population increases the risk of skull penetration with pin placement. Low body weight decreases resistance to traction, and lax ligaments and underdeveloped musculature increase the risk of over-distraction. Biparietal sets of bur holes with 22-gauge wire have been used to achieve skull purchase in infants [40]. For slightly older children, the use of a halo ring with eight to ten pins may be appropriate. Weight should be administered judiciously with frequent neurological exami- nations and radiographic imaging.

Halo immobilization has been reported in children as young as 7 months with ten pins placed to finger-tightness only [64]. Children aged 16 and 24 months were also immobilized successfully in halos with 2 ft lb of torque applied at each of ten pins [64]. Minor complications such as pin site infections are common [31]. Mandabach *et al*. reported successful fusion of eight of ten odontoid epiphyseal fractures managed in a halo [61]. This group recommends 1 ft lb of torque per year of age until 5 ftlb is reached. The thermoplastic Minerva body jacket is an alternative to halo immobilization in the very young. This device permits 2.1° of flexion-extension compared with 1.3° with a halo vest [61]. No pins are used and no artifact is created on MRI and CT scan.

Conclusions

Appropriate management of cervical spine trauma in children requires an understanding of the unique anatom- ical, biomechanical, radiographic, and pathophysiological characteristics of pediatric patients. Almost all literature on this subject is class III standard. There are many areas for further study, including the use of steroids in pediatric spinal cord injury, optimization of neck clearance in head-injured pediatric patients, and the appropriate management of SCIWORA. The relative rarity of pediatric cervical spine injuries demands multicenter involvement for well-designed studies.

Conflict of Interest

Not available

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