World Neurosurgery: X 20 (2023) 100235

Contents lists available at ScienceDirect

World Neurosurgery: X

journal homepage: www.journals.elsevier.com/world-neurosurgery-x

Relationship of cervical soft tissue injury and surgical predication following pediatric cervical spinal trauma and its sequelae on long-term neurologic outcome

Jasmine L. Hect[a], Michael M. McDowell[a,b,*], Daryl Fields[b], Stephanie Greene[a,b]

[a] Department of Neurosurgery, Children's Hospital of Pittsburgh, Pittsburgh, USA
[b] Department of Neurosurgery, University of Pittsburgh Medical Center, Pittsburgh, USA

ARTICLE INFO

Keywords:
Trauma
Cervical spine injury
MRI

1. Introduction

Evaluation of cervical spinal trauma (CST) in the pediatric trauma patient continues to vary widely across institutions due to the lack of high-quality evidence-based recommendations to guide standardization efforts.[1,2] Level II evidence has driven recommendations outlining first line imaging via X-ray and computed tomography (CT)[3] when indicated, both of which have demonstrated high sensitivity and specificity for cervical spinal injury.[4–10] Many studies suggest reserving magnetic resonance imaging (MRI) for patients with persistent neurologic deficits in the absence of radiographic findings, but recommendations remain based on level III evidence.[6,10–13] Prospective study of cervical imaging following CST in adults has shown that cervical CT is satisfactory for the identification of clinically significant injuries.[14] The role of MRI following negative CT remains nebulous, particularly for the purpose of cervical spine clearance.

MRI utilization varies across institutions, and it is often used as a first- or second-line assessment for the evaluation of operative candidacy in the pediatric CST patient.[2] The types of cervical soft tissue injuries best captured by MRI include ligamentous disruption, but identification of this can be confounded by soft tissue edema or hemorrhage.[13,15] MRI is often acquired at this center when there is suspicion of injury or instability of the craniocervical junction (CCJ), and when CT and Xray are negative but neck pain or neurologic complaints persist. While MRI is useful for describing soft tissue injuries and may aid in prognostication or surgical planning in the setting of neurological deficits,[11] overuse of MRI is associated with a high rate of false positive findings[4] and may result in an unnecessary cost burden with no added benefit to the patient and potentially additional burden due to the placement of unnecessary activity restrictions and collaring requirements. Data presented here provide a detailed characterization of MRI soft tissue findings after CST in a pediatric patient population and detail the relationship of MRI soft tissue injury to cervical spine clearance, neurologic deficit, and operative prognostication. Furthermore, data examine the utility of cervical CT or MRI imaging cervical spine clearance and operative prognostication for pediatric CST patients.

2. Methods

A post-hoc analysis of a prospectively collected database of pediatric patients less than 20 years old sustaining trauma was performed on a subset of patients who were screened for cervical spinal injuries at the Children's Hospital of Pittsburgh of UPMC, between January 1, 2010 and December 31, 2019. This study was approved as part of an institutional IRB for pediatric trauma research (STUDY19040084). A cohort of 543 patients with CST were identified within the trauma database. Patients were excluded if they did not have MRI of their cervical spine within 48 h of admission ($n = 239$) or if they had surgery for cervical spine instrumentation prior to MRI ($n = 4$). Three patients were identified who died from traumatic injuries. Two were excluded as their death was not attributable to injury to the cervical spine. The final retrospective cohort included 258 pediatric patients. Mechanisms of injury were defined as

* Corresponding author. Pediatric Neurosurgery Fellow, Division of Neurological Surgery, UPMC Children's Hospital of Pittsburgh, Pittsburgh, PA, 15213, USA.
E-mail address: mcdowellmm2@upmc.edu (M.M. McDowell).

https://doi.org/10.1016/j.wnsx.2023.100235
Received 17 October 2022; Received in revised form 2 June 2023; Accepted 12 June 2023

vehicular, accidental non-vehicular, or assault, which included cases of non-accidental trauma. Accidental non-vehicular traumas included falls, sports-related injuries, and recreational motorized vehicle accidents. Patients requiring surgery for fixation with or without decompression were identified ($n = 27$).

Chart review was performed to supplement data from the spine trauma database, including patient demographic information, imaging, radiologic reports, clinical findings at presentation, surgical intervention, follow-up, and long-term outcomes. Extraction of data from radiologic reports included descriptions of fracture, instability, and soft tissue injury. X-ray and CT imaging of the cervical spine were reviewed and considered "positive" if a radiologic abnormality was noted, not including congenital abnormalities. Different types of soft tissue injuries were categorized from MRI reports, including peri-vertebral injury (anterior and posterior longitudinal ligaments), injury to posterior ligamentous complex (interlaminar, ligamentum flavum, interspinous, supraspinous or nuchal ligaments), posterior paraspinous muscle edema, craniocervical (apical and alar) ligamentous injury (including edema or overt tear), cord edema, epidural or subdural spinal hematoma, intervertebral disc injury, and cord contusion (parenchymal hemorrhage).

At our institution, patients receive CT or X-ray as part of initial trauma workup when presenting with injuries mechanistically capable of causing cervical spine injury. A subset of patients also underwent flexion/extension X-ray for assessment of dynamic instability. All patients with persistent complaints of neurological symptoms, all patients with neurological deficits, patients with an unreliable neurological exam, and any patient with persistent moderate to severe neck pain but a negative cervical spine CT undergo MRI.

Neurologic complaint associated with CST was categorized based on the duration of symptoms: transient (resolved prior to arrival), persistent $<$24 h, or persistent $>$24 h. Symptoms included non-focal and focal complaints, including cervical radiculopathy, paresthesia, or anesthesia below level of injury. Cervical ASIA grading[16] was determined based on severity and extent of neurologic deficit findings at the time of admission, at 3, 6, and 12 months, and at longest follow-up. For univariate and multivariate analyses ASIA scores were binarized to "poor outcome" or "good outcome", where ASIA A, B, C were considered "poor outcome" and ASIA E or D were considered "good outcome". Death was also considered a poor admission outcome if related to cervical injury ($n = 1$).

Follow-up data from 3-, 6-, and 12-month visits included cervical imaging, presence of cervical strain, and presence of cervical instability. Cervical strain at follow-up was defined as significant persistent neck pain or muscle spasm resulting in limited range of motion. Flexion extension x-rays were acquired at follow-up to assess for instability.

Furthermore, overall positive versus negative sensitivity and specificity of cervical CT and MRI were calculated to test the relative screening ability for need of internal or external stabilization in this retrospective cohort. Radiologic reports were rated for description of unstable osseous or ligamentous injury. Instability of the cervical spine was defined as injury requiring surgery for stabilization or strict external fixation due to the finding, including Type II odontoids, Hangman fracture, or C2 synchondrosis fracture, severe kyphotic angulation or subluxation at any level, unilateral jumped facet, bilateral locked facets, or evidence of atlanta-occipital dislocation or ligamentous instability, following prior work.[4] Sensitivity and specificity were calculated for abnormal ("positive") CT and MRI, in addition to instability on CT and instability on MRI.

Shapiro–Wilk test of normality was used to guide selection of parametric or non-parametric analysis. Univariate analysis was performed comparing surgical and non-surgical patients, as well as good (ASIA D or E) and poor outcomes (ASIA A, B, or C) via Mann–Whitney, Kruskal–Wallis, chi-square, and Fisher's exact test as appropriate. Multivariate analysis via logistic regression was performed on appropriate variables with a p value of $\leq$0.2 using the saturated model technique. Statistical tests were performed using the Statistical Analysis System (SAS, version 9.4).

3. Results

Of the 258 patients, 27 (10.5%) underwent cervical spine surgery and six (2.3%) underwent external fixation with placement of halo. Average age at presentation for all patients was 11 $\pm$ 5.8 years, range 7 days–19.6 years. Ninety-two (35.7%) patients were female. Accidental (non-vehicular) trauma, as defined as all non-vehicular or assault accidental injuries (see Methods), was most common (66.9%, $n = 172$), followed by vehicular trauma (19.8%, $n = 51$) and assault (13.2%, $n = 34$). Of the 34 assault cases, 32 (94%) were coded as non-accidental trauma. Cervical spine injuries caused by vehicular trauma were more likely to require surgery (12/51 (23.5%); $p = 0.001$), while other injury mechanisms were not significantly associated with an increased surgical requirement (Table 1).

3.1. Clinical presentation

Ninety-eight (38%) patients presented with significant neck pain and tenderness to palpation following their trauma. One hundred and four patients (40.3%) experienced neurologic deficit of varied duration and severity, including 18 (7%) patients with transient symptoms that resolved prior to arrival in the emergency department, 50 (19.4%) with symptoms on arrival that resolved within 24 h, and 36 (14%) patients had symptoms that persisted $>$24 h. Zero patients were managed surgically if their neurologic complaint resolved prior to arrival or within 24 h, compared to 40.7% who underwent surgery with persistent neurologic symptoms ($p < 0.001$).

Eight patients were admitted with ASIA A, B, or C, including four ASIA A, one ASIA B, and two ASIA C. One patient died secondary to high cervical spine injury. Four patients were admitted as ASIA D. There were zero patients with persistent neurologic deficit localized to the cervical spine in the absence of radiographic findings. While two patients had neurologic complaints persisting $>$24 h in the absence of cervical x-ray and CT findings, one was found to have a brachial plexus injury and the other found to have T11 spinal cord transection, making the rate of spinal cord injury without radiographic abnormality (SCIWORA) zero percent in this cohort.

Fifty-nine of 258 patients experienced clinically significant head trauma, defined as abnormal acute cranial radiographic finding. Median sample-wise Glascow coma score (GCS) was 15 (12–15). GCS was not significantly different between surgical groups, including median GCS 15 (13–15) in those without surgical spine injury and GCS 13 (3–14) in surgical patients ($p = 0.11$). A total of 11.2% ($n = 29$) of patients were sedated and intubated prior to arrival. These patients were no more likely to require spine surgery than patients for whom a neurological exam was feasible (17.9% vs 9.6%, $p = 0.19$), and were not more or less likely to undergo cervical x-ray (55.2% vs 39.3%, $p = 0.11$) or CT (70% vs 71.4%, $p = 0.88$).

3.2. Cervical imaging characteristics

A total of 55 (21.3%) patients had X-ray and MRI, 98 (38%) had CT and MRI, 83 (32.2%) had Xray, CT, and MRI, and 22 (8.5%) patients had only MRI of the cervical spine. Positive imaging findings were seen in 27 of 139 (19.7%) patients with cervical X-ray, of which 10 were unstable injuries. Additionally, a total of 16 patients underwent flexion/extension X-rays, of which two patients appeared to have evidence of instability at the craniocervical junction; only one patient demonstrated CCJ ligamentous injury on subsequent MRI. CT was positive in 79 of 181 (43.6%) patients, and identified unstable injury in 40 cases. For the 27 surgical patients, all demonstrated clinically significant radiographic injury requiring surgery on CT except one. One surgical patient with congenital cervical canal stenosis subsequently underwent MRI following a negative CT because of persistent decreased strength in bilateral upper extremities acutely following CST which demonstrated exacerbated stenosis at C2–C3 due to a bulging disc which resulted in complete effacement of

Table 1
Univariate analysis of cervical surgery predictors.

	Total $n = 258$	No surgery $n = 231$	Surgery for CST $n = 27$	p-value
Age, mean (IQR)	13.20 (6.56–15.88)	13.11 (6.36–15.67)	15.24 (7.56–16.24)	0.14
Female	91 (35.3%)	85 (36.8%)	6 (22.2%)	0.13
Mechanism of injury				
Accidental non-vehicular	172 (66.9%)	157 (68.3%)	15 (55.6%)	0.18
Vehicular trauma	51 (19.8%)	39 (17.0%)	12 (44.4%)	<0.001
Assault	34 (13.2%)	34 (14.8%)	0 (0.0%)	0.032
Admission neurologic deficit				
(ASIA A, B, or C)	8 (3.1%)	2 (0.9%)	6 (22.2%)	<0.001
Admission neurologic complaint	104 (40.3%)	93 (40.3%)	11 (40.7%)	0.96
Resolved prior to arrival	18 (7.0%)	18 (7.8%)	0 (0.0%)	0.13
Resolved <24 h	50 (19.4%)	50 (21.6%)	0 (0.0%)	0.004
Persisted >24 h	36 (14.0%)	25 (10.8%)	11 (40.7%)	<0.001
Admission neck pain	98 (38.0%)	90 (39.0%)	8 (29.6%)	0.34
Admission cervical injury X-ray	27 (19.7%)	20 (16.0%)	7 (58.3%)	<0.001
Admission cervical injury CT	79 (43.6%)	53 (34.2%)	27 (100.0%)	<0.001
Admission cervical fracture	45 (17.4%)	31 (13.4%)	14 (51.9%)	<0.001
Admission MRI soft tissue injury	117 (45.3%)	90 (39.0%)	27 (100.0%)	<0.001
Number of positive findings, median (IQR)	2 (1–3)	1 (1–2)	4 (2–5)	<0.001
Peri-vertebral swelling	55 (47.0%)	36 (40.0%)	19 (70.4%)	0.006
Posterior spinous ligament injury	50 (42.7%)	35 (38.9%)	15 (55.6%)	0.12
Posterior paraspinous muscle	39 (33.3%)	30 (33.3%)	9 (33.3%)	1.00
Joint injury	29 (24.8%)	19 (21.1%)	10 (37.0%)	0.093
Craniocervical ligament injury[a]	25 (21.4%)	14 (15.6%)	11 (40.7%)	0.005
Craniocervical ligament tear	10 (8.5%)	3 (3.3%)	7 (25.9%)	0.001
Craniocervical ligament no tear	15 (12.8%)	11 (12.2%)	4 (14.8%)	0.75
Cord edema	23 (19.7%)	12 (13.3%)	11 (40.7%)	0.002
Disc injury	18 (15.4%)	10 (11.1%)	8 (29.6%)	0.019
Extra-axial spinal hematoma	18 (15.4%)	9 (10.0%)	9 (33.3%)	0.003
Cord contusion	7 (6.0%)	2 (2.2%)	5 (18.5%)	0.007
Halo placed	10 (3.9%)	6 (2.6%)	4 (14.8%)	0.013
Length of hospitalization (days)	2 (1–7)	2 (1–5)	8 (5–22)	<0.001
Inpatient rehabilitation	28 (10.9%)	18 (7.9%)	10 (37.0%)	<0.001
C-collar on discharge	173 (67.3%)	151 (65.7%)	22 (81.5%)	0.097
Length of immobilization (weeks)	4.93 (2.36–7.29)	4.00 (2.14–6.57)	9.86 (6.29–16.86)	<0.001
3-month follow-up	193 (74.8%)	167 (72.3%)	26 (96.3%)	0.007
ASIA A, B, or C	6 (3.1%)	1 (0.6%)	5 (19.2%)	<0.001
Instability	2 (1.6%)	1 (0.9%)	1 (5.0%)	0.29
6-month follow-up	50 (19.5%)	35 (15.3%)	15 (55.6%)	<0.001
ASIA A, B, or C	3 (6%)	1 (3%)	2 (13%)	0.21
Instability	4 (8%)	2 (15%)	2 (22%)	1.00
12-month follow-up	47 (18.5%)	29 (12.8%)	18 (66.7%)	<0.001
ASIA A, B, or C	4 (9%)	0 (0%)	4 (22%)	0.017
Instability	2 (11%)	2 (20%)	1 (6%)	0.54
Longest follow-up (months)	1.63 (0.60–9.12)	1.43 (0.53–6.04)	24.45 (4.88–40.21)	<0.001
ASIA A, B, or C	7 (2.7%)	2 (0.9%)	5 (18.5%)	<0.001
Instability	3 (2.6%)	2 (2.1%)	1 (4.5%)	0.47

[a] Craniocervical ligamentous injury includes any indication of edema or noticeable tear noted in radiologic reports.

CSF spaces and increased cord signal concerning for myelomalacia.

MRI captured soft tissue injury in 117 (45.3%) pediatric CST patients that ranged in severity. In those with positive MRI findings, the most frequent soft tissue injuries were peri-vertebral edema (47%), posterior spinous ligament injury (42.7%), posterior paraspinous muscle edema (33.3%), joint injury (24.8%), occipital cervical ligament tear or swelling (20.5%), cord edema (19.7%), extra-axial spinal hematoma (15.4%), intervertebral disc injury (15.4%), and cord contusion (6%) (Table 1).

Patients with severe neurologic deficit (ASIA A, B, or C) on admission were found to have cord edema in 100% of cases ($n = 7$, 100% vs 7.2%, $p < 0.001$), and were more likely to have intraparenchymal hemorrhage (contusion) (28.6% vs 1.6%, $p = 0.009$), intervertebral joint capsule injury (42.9% vs 10.4%, $p = 0.033$) and posterior spinous ligament injury (57.1% vs 18.4%, $p = 0.028$) than patients with ASIA E or D.

3.3. Management

Twenty-seven patients underwent cervical spine surgery to address instability and/or spinal cord compression by displaced fracture and six patients underwent external fixation. A total of 13 patients underwent surgery for injuries at the level of the craniocervical junction (CCJ) and 14 for sub-axial injuries. CCJ injuries included Type II odontoids fracture, one case of cord compression with concern for myelomalacia in the setting of bulging disc and congenital cervical canal stenosis, six atlanta-occipital dislocations (AOD), two translational atlanta-occipital subluxations, and three cases of craniocervical ligament disruption resulting in instability without malalignment. One patient underwent surgery for a traumatic disc herniation causing cervical cord compression.

Surgical patients were more likely to have significant X-ray (58.3% vs 16%, $p < 0.001$) or CT (100% vs 34.2%, $p < 0.001$) findings and have neurologic symptoms >24 h (40.7% vs 10.8%, $p < 0.001$), compared to non-surgical patients. Among patients with MRI soft tissue findings, surgical patients had a greater total number of soft tissue abnormalities compared to non-surgical patients (4 ± 3.5 vs 1 ± 2 $p < 0.001$), including peri-vertebral edema (70.4% vs 40%, $p = 0.006$), injury to intervertebral disc (29.6% vs 11.1%, $p = 0.019$), craniocervical ligament tear (25.9% vs 3.3%, $p = 0.001$), as well as cervical spinal cord edema (40.7% vs 13.3%, $p = 0.002$), cord contusion (parenchymal hemorrhage; 18.5% vs 2.2%, $p = 0.007$), and epidural or subdural spinal hematoma (33.3%, 10%, $p = 0.003$) (Table 1). Patients with craniocervical ligament injury, but no tear, were not more likely to have surgery (12.2% vs 14.8%, $p = 0.75$).

Independent variables with an association ($p < 0.2$) with outcome on univariate analysis were assessed via multivariate logistic regression. The multivariate analysis performed for independently predicting the need for surgery included age, female gender, persistent neurologic deficit, vehicular trauma injury mechanism, positive cervical CT, and soft tissue injury on MRI. Ligamentous injury captured on MRI most predictive of surgery included craniocervical ligament injury. Independent predictors of surgery included persistent neurologic deficit >24 h (OR 6.02, p = 0.003), cervical spine CT demonstrating injury (OR 5.2, p = 0.013), and MR imaging demonstrating soft tissue injury (OR 16.3, p = 0.0086), but not age (OR 1.04, p = 0.45), female gender (OR 0.71, p = 0.59), or injury mechanism (OR 2.6, p = 0.085) (Table 4).

3.4. Cervical immobilization

A total of 224 of 257 patients discharged did not require surgery or external fixation. Of these, 31 patients had cervical fractures managed conservatively, including 27 (87.1%) discharged with cervical spine immobilization for an average of 7.2 ± 4.1 weeks. Of non-surgical patients without fractures ($n = 199$), 71 (35.7%) had their cervical spine cleared prior to hospital discharge. In cases of non-operative injury or cervicalgia ($n = 128$), immobilization was maintained for an average of 5.1 ± 9.8 weeks. Patients with neck pain on admission were most likely to be discharged with a rigid external orthosis (47.7% vs 18.3%, $p < 0.001$), despite no difference in neurologic complaints (46.9% vs 35.2%, $p = 0.11$), positive cervical x-ray (11.3% vs 7.5%, $p = 0.52$), positive CT (24.1% vs 15%, $p = 0.24$), or soft tissue findings on MRI (35.9% vs 28.2%, $p = 0.26$). Patients discharged with cervical collars were more likely to have 3-month follow-up (81.2% vs 47.9%, $p < 0.001$), but did not demonstrate a greater rate of cervical strain (3.9% vs. 0%, $p = 0.57$) or instability (0% vs 0%), compared to patients who had their cervical spine cleared before discharge (Table 3).

Two patients discharged with cervical collars required surgery following discharge. Both patients had positive CT imaging and MRI demonstrating the injury during their initial work-up. One patient with known congenital cervical stenosis and prior CST underwent an elective laminectomy and bilateral facetectomies 19 days after discharge, after allowing for resolution of edema surrounding a spinal cord contusion identified on MRI in the region of stenosis during their admission. This patient required C2-T2 posterior instrumented fusion 5 months later for post-laminectomy kyphosis. Another patient underwent posterior fusion for worsening deformity after 1 month of rigid immobilization in a cervical collar for C3 and C4 sagittal vertebral body fracture.

3.5. Clinical outcomes

Of the 193 patients seen at 3-month follow-up, six (3.1%) had a persistent neurologic deficit and two (1.6%) had radiographic evidence of persistent cervical instability, both of whom remained in rigid external orthosis ($n = 1$) or fixation (halo; $n = 1$) and were asymptomatic and neurologically intact at follow-up. Fifty patients were seen at 6-months, of whom three (6%) had persistent neurologic deficit and four (8%) had evidence of instability, including the two patients with instability at 3-months, one patient with Down syndrome with incomplete fusion of O–C2 performed for atlantoaxial dislocation who was prescribed to remain in halo another 3-months, and one patient who underwent C2-T2 posterior fusion 13 days after follow-up imaging revealed worsening of post-laminectomy kyphosis. Finally, 47 patients (18.4%) were seen at 1-year follow-up, four (9%) had persistent neurologic deficit and the two (4.3%) patients with instability at 3- and 6-month follow-up had evidence of persistent instability (Table 1). One of these patients did improve without surgery, and the other patient required prolonged rigid external fixation due to slow O–C2 fusion.

Of the 197 patients with follow-up, six patients were ASIA A, B, or C at longest follow-up. Compared to ASIA D or E, ASIA A, B or C patients were most likely to have had persistent neurologic deficit on admission (100% vs 0.5%, $p < 0.001$) and soft tissue injury on MRI (100% vs 50.3%, $p = 0.029$), specifically cord edema (100% vs 17.7%, $p < 0.001$) and cord contusion (33.3% vs 4.2%, $p = 0.039$) (Table 2). Of the four patients who originally presented as ASIA A, two improved to ASIA C over the course of follow-up; one patient with ASIA B at presentation improved to ASIA E; two patients ASIA C at presentation did not improve and one improved to ASIA D; and of the three patients with ASIA D on admission, one improved to ASIA E.

Multivariate analysis performed for predicting persistent neurologic deficit at longest follow-up included poor pre-operative ASIA grade (OR 20.2, p = 0.01), accidental non-vehicular trauma (OR 2.6, p = 0.39), vehicular trauma (OR 1.02, p = 0.99), CT imaging of cervical spine demonstrating injury (OR 0.53, p = 0.27), and total number of soft tissue MRI imaging findings (OR 1.6, p = 0.0006) (Table 5). MRI findings of cord edema or cord contusion were most likely associated with neurologic deficit (Table 2).

4. Discussion

This study found that 1) ligamentous injuries identified by MRI are strongly associated with operative need and also strongly predict the likelihood of permanent neurological deficits; 2) Patients discharged with cervical collars based on MRI findings alone were unlikely to require operative intervention in the future for cervical instability; 3) MRI provides little operative predictive value beyond the presence of neurological deficit or CT abnormality. While we found that cervical CT imaging was able to capture instability with good sensitivity and specificity, logistic regression of surgical predictors demonstrated that presence of soft tissue injury, captured on MRI, to be predictive of operative need, specifically craniocervical ligamentous injury. The number of soft tissue injuries was found to be predictive of neurologic outcomes, intuitively this was driven predominantly by the presence of cord edema or contusion following initial injury. Data reinforce MRI as useful for describing soft tissue injuries such as epidural hematoma or intervertebral disc herniation, surgical planning, and utility in prediction of functional outcomes in the setting of neurological deficits. The data presented here suggest while MRI is useful in refining an operative plan, CT is sufficient to determine whether a patient needs surgery in the absence of a neurologic deficit, in line with prior reports.[3,4,17]

Evaluation of the pediatric CST trauma patient for clearing the cervical spine typically includes Xray and/or CT, but when initial imaging is negative despite persistent symptoms, MRI is often obtained to rule out injury.[2,4,12] The literature suggests that CT performs better as an initial screening test compared to X-ray.[4,6,9,18] This report found 100% sensitivity and 95% specificity of CT as a screening test to identify patients with unstable injury. In comparison, MRI demonstrated 100% sensitivity and 89% specificity for detection of unstable injury. When considering the sensitivity and specificity of CT and MRI to detect injuries of any severity related to CST, there is 100% sensitivity and 68% specificity in the case of CT and 60% specificity of MRI. These data support prior studies demonstrating similar findings of relatively high false positives rate and overcalling of operative-level injury with MRI,[2,4,19] including 100% sensitivity of CT and 95–100% specificity for the identification of unstable CST.[4,9]

Clearance of the cervical spine is made difficult by the unique biomechanical properties of the pediatric spinal column and craniocervical junction (CCJ), including larger head size and highly flexible spine, which predispose children to dislocation injury.[20] Outside of preoperative planning, these data suggest reserving MRI for patients with persistent neurologic deficit (>24 h). In line with prior reports, there was a low prevalence of cervical instability in this high-risk pediatric cohort overall.[4] Additionally, CT had high sensitivity and specificity, while MRI had a relatively greater false-positive rate. These data align with the pediatric literature suggesting CT or plain radiographs as the first-line trauma screening tool, although MRI is recommended to rule out unstable injury in the setting of negative CT and persistent neurologic symptoms.[4,21] Prior work suggests that ligamentous instability after negative radiographic imaging may be best ruled out using flexion-extension X-ray with fluoroscopy as opposed to MRI.[4] A small subset of patients ($n = 16$) underwent flexion-extension X-ray during

Table 2
Univariate analysis of persistent neurologic outcomes predictors.

	Total $n = 197$	ASIA D/E $n = 191$	ASIA A/B/C $n = 6$	p-value
Age, mean (IQR)	13.25 (6.11–15.88)	13.28 (5.73–15.88)	12.71 (7.87–16.14)	1.00
Female	71 (36.0%)	68 (35.6%)	3 (50.0%)	0.67
Mechanism				
Accidental non-vehicular	128 (65.0%)	123 (64.4%)	5 (83.3%)	0.67
Vehicular trauma	40 (20.3%)	39 (20.4%)	1 (16.7%)	1.00
Assault	29 (14.7%)	29 (15.2%)	0 (0.0%)	0.59
Neurologic deficit admission (ASIA A, B, or C)	7 (3.6%)	1 (0.5%)	6 (100.0%)	<0.001
Admission Neuro Complaint	79 (40.1%)	73 (38.2%)	6 (100.0%)	0.004
Resolved prior to arrival	15 (7.6%)	15 (7.9%)	0 (0.0%)	1.00
Resolved <24 h	35 (17.8%)	35 (18.3%)	0 (0.0%)	0.59
Persisted >24 h	29 (14.7%)	23 (12.0%)	6 (100.0%)	<0.001
Admission neck pain	76 (38.6%)	75 (39.3%)	1 (16.7%)	0.41
Admission cervical injury X-ray	21 (20.2%)	19 (19.0%)	2 (50.0%)	0.18
Admission cervical injury CT	71 (50.0%)	66 (48.2%)	6 (100.0%)	0.058
Admission cervical fracture	43 (21.8%)	40 (20.9%)	3 (50.0%)	0.12
Admission MRI soft tissue injury	102 (51.8%)	96 (50.3%)	6 (100.0%)	0.029
Number of positive findings, median (IQR)	2 (1–3)	2 (1–3)	3.5 (2–5)	0.036
Peri-vertebral swelling	51 (50.0%)	48 (50.0%)	3 (50.0%)	1.00
Posterior spinous ligament injury	46 (45.1%)	43 (44.8%)	3 (50.0%)	1.00
Posterior paraspinous muscle	33 (32.4%)	31 (32.3%)	2 (33.3%)	1.00
Joint injury	26 (25.5%)	24 (25.0%)	2 (33.3%)	0.64
Cord edema	23 (22.5%)	17 (17.7%)	6 (100.0%)	<0.001
Craniocervical ligament injury	22 (21.6%)	21 (21.9%)	1 (16.7%)	1.00
Extra-axial spinal hematoma	17 (16.7%)	16 (16.7%)	1 (16.7%)	1.00
Disc injury	16 (15.7%)	14 (14.6%)	2 (33.3%)	0.24
Craniocervical ligament tear	10 (9.8%)	10 (10.4%)	0 (0.0%)	1.00
Cord contusion	6 (5.9%)	4 (4.2%)	2 (33.3%)	0.039
Length of hospitalization (days)	3 (1–8)	3 (1–7)	18.5 (7–40)	0.002
Inpatient rehabilitation	27 (13.8%)	21 (11.1%)	6 (100.0%)	<0.001
Halo placed	9 (4.6%)	9 (4.7%)	0 (0.0%)	1.00
C-collar on discharge	151 (76.6%)	147 (77.0%)	4 (66.7%)	0.63
Length of immobilization (weeks)	4.93 (2.29–7.43)	4.71 (2.29–7.14)	14.14 (8.29–158.14)	0.014
Longest follow-up (months)	1.63 (0.60–9.12)	1.59 (0.56–7.73)	38.69 (13.87–56.97)	0.005

Table 3
Cervical spine clearance and patient outcomes.

	Total $n = 199$	C-spine cleared $n = 71$	C-spine immobilized $n = 128$	p-value
Age	12.84 (5.10–15.67)	11.27 (2.18–14.96)	13.49 (7.07–15.90)	0.044
Female	76 (38.2%)	22 (31.0%)	54 (42.2%)	0.12
Mechanism				
Accidental non-vehicular	138 (69.3%)	49 (69.0%)	89 (69.5%)	0.94
Vehicular trauma	29 (14.6%)	9 (12.7%)	20 (15.6%)	0.57
Assault	32 (16.1%)	13 (18.3%)	19 (14.8%)	0.55
Neurologic deficit admission (ASIA A, B, or C)	1 (0.5%)	1 (1.4%)	0 (0.0%)	0.36
Admission Neuro Complaint	85 (42.7%)	25 (35.2%)	60 (46.9%)	0.11
Resolved prior to arrival	17 (8.5%)	4 (5.6%)	13 (10.2%)	0.27
Resolved <24 h	47 (23.6%)	13 (18.3%)	34 (26.6%)	0.22
Persisted >24 h	21 (10.6%)	8 (11.3%)	13 (10.2%)	0.81
Admission neck pain	74 (37.2%)	13 (18.3%)	61 (47.7%)	<0.001
Admission cervical injury X-ray	11 (9.9%)	3 (7.5%)	8 (11.3%)	0.52
Admission cervical injury CT	27 (21.3%)	6 (15.0%)	21 (24.1%)	0.24
Admission cervical fracture	0 (0.0%)	0 (0.0%)	0 (0.0%)	
Admission MRI soft tissue injury	66 (33.2%)	20 (28.2%)	46 (35.9%)	0.26
Length of immobilization (weeks)	3.21 (2.14–6.14)		3.21 (2.14–6.14)	
Discharge to inpatient rehabilitation	15 (7.6%)	5 (7.0%)	10 (7.9%)	0.83
Length of hospitalization (days)	2 (1–5)	2 (1–8)	2 (1–3)	0.026
3-month follow-up	138 (69.3%)	34 (47.9%)	104 (81.2%)	<0.001
ASIA A, B, or C	1 (0.7%)	1 (3.0%)	0 (0.0%)	0.24
Instability	0 (0%)	0 (0%)	0 (0%)	
6-month follow-up	29 (14.6%)	11 (15.7%)	18 (14.1%)	0.83
ASIA A, B, or C	1 (3%)	1 (9%)	0 (0%)	0.38
Instability	1 (12%)	0 (0%)	1 (20%)	1.00
12-month follow-up	25 (12.8%)	7 (10.1%)	18 (14.2%)	0.51
ASIA A, B, or C	0 (0%)	0 (0%)	0 (0%)	
Instability	2 (33%)	0 (0%)	2 (40%)	1.00
Longest follow-up (months)	1.16 (0.50–5.81)	2.52 (1.03–11.84)	0.90 (0.46–3.28)	<0.001
ASIA A, B, or C	1 (0.5%)	1 (1.4%)	0 (0.0%)	0.36
Instability	2 (3%)	0 (0%)	2 (3%)	1.00

Table 4
Logistic regression of predictors for surgery and persistent neurologic deficits.

	OR	CI	*p* Value
Age	1.04	0.94–1.2	0.45
Female	0.71	0.20–2.5	0.59
Persistent Neurological Deficit (>24h)	6.02	1.9–19.3	0.003
Vehicular Trauma	2.6	0.88–7.6	0.085
Positive CT	5.2	1.4–19.1	0.013
Soft tissue injury MRI	16.3	2.0–131.2	0.0086

Table 5
Predictors of persistent neurological deficit at longest follow-up.

	OR	CI	*p* Value
Admission ASIA Score	20.2	2.03–201.0	0.01
Accidental Non-vehicular Trauma	2.6	0.29–22.9	0.39
Vehicular Trauma	1.02	0.092–11.2	0.99
Positive CT	0.53	0.17–1.6	0.27
Number of cervical soft tissue injuries	1.6	1.2–2.1	0.0006

their work-up for assessment of dynamic instability, of which only two were found to have suspicion of instability. In certain circumstances MRI may be needed, such as the unconscious patient or patient that is unable to cooperate with a neurologic examination. In this cohort, several patients with surgically relevant ligamentous injuries were identified on screening CT prior to MRI. One reason this may be is the increased use of high-resolution CT and overall better visualization of soft tissue with CT than in the past. The rate of SCIWORA, defined as neurologic deficit in the setting of negative radiographic imaging, was found to be zero percent in this population; all patients with persistent neurologic deficit had radiologic correlation. SCIWORA was named prior to the advent of MRI; thus, the classic definition would consider patients with negative X-ray and CT but with abnormalities on MRI to have SCIWORA. By this definition, MRI identified abnormalities in two of twelve patients with negative X-ray and CT with persistent neurologic complaint (>24 h), including one with intrathecal hematoma and one with cord contusion. Neither patient was deemed to require surgical intervention, and the neurologic deficits resolved prior to discharge. All surgical patients had persistent neurologic deficit or abnormal CT finding. When a reliable, normal neurological exam is available and the patient has received a cervical CT scan, MRI should not be routinely obtained on patients with symptoms other than neurological deficits. In the absence of clear findings of neurologic deficit or CT abnormality, collar usage should be for comfort only and not strictly enforced.

In line with this assertion, these data support that cervical spine clearance may safely be performed in the case of absent or resolved neurologic deficit and no X-ray or CT abnormality in the conscious and oriented patient. Among non-surgical patients, rates of cervical instability and strain did not differ between those discharged with immobilization and those cleared in the hospital. Additional considerations may be needed in the case of very young patients, non-accidental trauma work-up, or osteopenia due to age, medication, or disorder. While soft tissue injuries in the absence of vertebral injury are reported to be more common in children, the relationship of the magnitude of soft tissue findings and need for cervical immobilization is poorly defined.[13] Strong evidence-based guidelines for pediatric patients addressing collar use or subspecialty referral for follow-up do not exist. Patients discharged with cervical collars for persistent midline cervical tenderness are very unlikely to experience new onset instability or spinal cord injury in the absence of Xray or CT findings,[22] and prolonged use of immobilization for cervicalgia alone may lead to prolonged symptoms.[23] In this study, patients with neck pain and soft tissue injury on MRI were less likely to have their cervical spine cleared before discharge, but there was no effect of duration of neurologic complaint at presentation upon likelihood of cervical collar at discharge. Patients discharged with collars were more likely to have neurosurgical follow-up, despite no difference in long-term rates of cervical strain or instability. This study suggests that cervical collar immobilization after pediatric CST and the referral to subspecialists for follow-up may be overutilized, and warrants additional investigation for the development of specific recommendations. The presence of cervicalgia alone should not be used to justify strict collar usage. Rather, collar usage for comfort only is more appropriate. This study suggests that immediate cervical spine clearance without further testing or the use of dynamic x-rays at the time of presentation is sufficient in cases without CT findings or neurological deficits.

MRI is frequently used to assess ligamentous injury at the CCJ, which is a rare but severe complication of pediatric CST. Pediatric patients incur atlantooccipital injuries 2.5 times more frequently than adults.[20] CT imaging may be sufficient for the assessment of instability,[24] although consensus has yet to be reached in the field. Gargas and colleagues analyzed the findings of cervical MRI after normal CT in pediatric patients with CST and found significant injuries requiring external fixation for stabilization of the craniocervical junction in 2.9% of cases.[25] In the current study, CT identified injury at the CCJ, including subluxation or ligamentous injury requiring stabilization, with a sensitivity and specificity of 81% and 91%. This suggests that operatively relevant CCJ injuries are detectable by CT with reliability. While non-operative cervical injuries are better characterized and captured on MRI, these injuries likely heal without immobilization and are unlikely to progress to instability, although this has not been specifically examined.

Regular use of MRI to explore soft tissue injuries should be reserved for patients with neurologic complaints in the setting of a negative CT of the cervical spine or a traumatic brain injury precluding identification of neurologic deficit, although remains useful for operative planning and extent of injury in severe cases. Severe neurologic deficit persisting beyond 24 h is more likely to require extensive inpatient rehabilitation.[26,27] All patients who presented with self-resolving neurologic complaints of relatively short duration, including paresthesia, paralysis, and/or anesthesia below the level of injury, were found to have negative imaging or non-operative injuries. Most experienced spontaneous resolution of neurologic symptoms within 24 h of their injury, which may represent mild degrees of transient neuropraxia following CST. Of patients requiring surgical intervention, those with epidural or subdural spinal hematoma, cord contusion, or injury to craniocervical ligaments were most likely to require surgery. Positive screening for unstable injury with CT imaging or persistent neurologic complaint demonstrated 100% sensitivity and 81% specificity for prediction of operative candidacy, including external fixation. Persistence of neurologic complaint greater than 24 h was also independently found to be predictive of surgical intervention. A study of cervical injury in adults by Tewari et al proposed that the chance of neurologic recovery depends directly on the degree of injury seen on MRI, where those who have mild injury or cord edema have the best prognosis, and those with spinal cord hemorrhage have the poorest.[15] In the data reported here, logistic regression identified poor pre-operative ASIA score (ASIA A, B, C) and total number of soft tissue findings on MRI as predictive of persistent deficit at long-term follow-up, with an odds ratio of 20.2 and 1.6,respectively. All 36 patients with persistent neurologic deficits >24 h were found to have soft tissue abnormalities on MRI, which were most frequently cord edema, peri-vertebral edema, and epidural or subdural spinal hematoma, among others. All patients with poor ASIA grading on admission exam had cord edema or contusion on initial MRI. The relative magnitude of soft tissue findings on MRI strongly predicted the risk of permanent neurological deficit independent of pre-operative ASIA score. Careful tabulation of ligamentous injuries may be valuable in the prognostication of cervical trauma in pediatric patients with persistent neurologic deficit or unstable injury.

The proposed imaging modalities are not without risk, and limiting all unnecessary imaging is encouraged. The drawbacks of X-ray and CT include radiation carrying a lifetime elevated risk of malignancy.[28,29] A recent study demonstrated that the median effective dose of radiation for cervical CT may be less than previously thought with modern scanners

(4.51 mSv (3.84–5.59), although the required dose increases with body size and radiation exposure should be limited regardless.[9] The use of energy-efficient CT scanners has also been shown to expose patients to less ionizing radiation despite more cuts per scan,[13] allowing for improved resolution and visualization of soft tissues. The risks of MRI include the need for sedation and intubation in many patients younger than 7 years, which include aspiration, unknown effects on cognition, and allergic reaction to sedating medications.[30,31] While these results show that the number of findings on MRI is strongly predictive of needing surgical intervention, CT provides superior bony detail for pre-operative planning and is more rapidly available for trauma screening.

4.1. Limitations

This study is limited by its single-center, post-hoc nature. The number of patients with neurologic deficit at follow-up was small, limiting the generalizability of the univariate and multivariate analyses. Further, follow-up length varied across our sample, where patients with more severe injuries were more likely to be followed through 1-year. Radiologic reports were taken from patient charts and raw imaging did not undergo dual rater judgement of a standardized set of imaging characteristics for the purposes of this study. Our calculations of sensitivity and specificity of CT for the detection of unstable injury are potentially biased as radiographic reviewers may have viewed CT and MRI simultaneously, although most often CT was acquired and reviewed acutely following presentation. Furthermore, surgical candidacy is determined through a multivariable decision-making process, which limits the generalizability of these findings and the use of clinical presentation and imaging for the prediction of surgical candidacy. These findings are also limited in generalizability to very young children in whom a neurologic exam may not be reliable. The calculation of sensitivity and specificity is potentially limited by the cohort inclusion criteria, which excluded all patients without MRI.

5. Conclusions

CT imaging appears sufficient for the identification of traumatic osseous and ligamentous pediatric cervical spine injuries that are sufficiently severe to require operative intervention, though MRI remains helpful in operative planning. The utility of screening neurologically intact patients with MRI to determine operative candidacy is found to be limited when a CT scan has been acquired and a reliable, normal neurological exam is available. Finally, in the cohort with severe injuries the quantity of soft-tissue injuries identified by MRI appears to be proportional to the probability of permanent neurological deficit, in line with prior reports.

CRediT authorship contribution statement

Jasmine L. Hect: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Michael M. McDowell:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Daryl Fields:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Stephanie Greene:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

None.

References

1. Pannu GS, Shah MP, Herman MJ. Cervical spine clearance in pediatric trauma centers: the need for standardization and an evidence-based protocol. *J Pediatr Orthop*. 2017;37:e145–e149.
2. Massoumi R, Wertz J, Duong T, Tseng C-H, Jen HC-H. Variation in pediatric cervical spine imaging across trauma centers—a cause for concern? *J Trauma Acute Care Surg.* 2021;91:641–648.
3. Herman MJ, et al. Pediatric cervical spine clearance: a consensus statement and algorithm from the pediatric cervical spine clearance working group. *J Bone Joint Surg Am*. 2019;101:e1.
4. Brockmeyer DL, Ragel BT, Kestle JRW. The pediatric cervical spine instability study. A pilot study assessing the prognostic value of four imaging modalities in clearing the cervical spine for children with severe traumatic injuries. *Childs Nerv Syst*. 2012;28:699–705.
5. Cui LW, Probst MA, Hoffman JR, Mower WR. Sensitivity of plain radiography for pediatric cervical spine injury. *Emerg Radiol*. 2016;23:443–448.
6. Holmes JF, Akkinepalli R. Computed tomography versus plain radiography to screen for cervical spine injury: a meta-analysis. *J Trauma*. 2005;58:902–905.
7. Hale DF, Fitzpatrick CM, Doski JJ, Stewart RM, Mueller DL. Absence of clinical findings reliably excludes unstable cervical spine injuries in children 5 years or younger. *J Trauma Acute Care Surg.* 2015;78:943–948.
8. Wang MX, Beckmann NM. Imaging of pediatric cervical spine trauma. *Emerg Radiol.* 2021;28:127–141.
9. Somppi LK, Frenn KA, Kharbanda AB. Examination of pediatric radiation dose delivered after cervical spine trauma. *Pediatr Emerg Care*. 2018;34:691–695.
10. Rozzelle CJ, et al. Management of pediatric cervical spine and spinal cord injuries. *Neurosurgery*. 2013;72(Suppl 2):205–226.
11. Pang D. Spinal cord injury without radiographic abnormality in children, 2 decades later. *Neurosurgery*. 2004;55:1325–1342. discussion 1342-1343.
12. Wang MX, Beckmann NM. Imaging of pediatric cervical spine trauma. *Emerg Radiol.* 2021;28:127–141.
13. Konovalov N, et al. Pediatric cervical spine injuries and SCIWORA: WFNS spine committee recommendations. *Neurospine*. 2020;17:797–808.
14. Resnick S, et al. Clinical relevance of magnetic resonance imaging in cervical spine clearance: a prospective study. *JAMA Surg*. 2014;149:934–939.
15. Tewari MK, et al. Diagnosis and prognostication of adult spinal cord injury without radiographic abnormality using magnetic resonance imaging: analysis of 40 patients. *Surg Neurol*. 2005;63:204–209.
16. Roberts TT, Leonard GR, Cepela DJ. Classifications in brief: American spinal injury association (ASIA) impairment scale. *Clin Orthop Relat Res*. 2017;475:1499–1504.
17. Schuster R, et al. Magnetic resonance imaging is not needed to clear cervical spines in blunt trauma patients with normal computed tomographic results and No motor deficits. *Arch Surg*. 2005;140:762–766.
18. Lin JT, Lee JL, Lee ST. Evaluation of occult cervical spine fractures on radiographs and CT. *Emerg Radiol*. 2003;10:128–134.
19. Oh A, et al. Changes in use of cervical spine magnetic resonance imaging for pediatric patients with nonaccidental trauma. *J Neurosurg Pediatr*. 2017;20:271–277.
20. Gopinathan NR, Viswanathan VK, Crawford AH. Cervical spine evaluation in pediatric trauma: a review and an update of current concepts. *Indian J Orthop*. 2018;52:489–500.
21. Hale AT, et al. X-ray vs. CT in identifying significant C-spine injuries in the pediatric population. *Childs Nerv Syst*. 2017;33:1977–1983.
22. Dorney K, et al. Outcomes of pediatric patients with persistent midline cervical spine tenderness and negative imaging result after trauma. *J Trauma Acute Care Surg*. 2015;79:822–827.
23. Muzin S, Isaac Z, Walker J, Abd OE, Baima J. When should a cervical collar be used to treat neck pain? *Curr Rev Musculoskelet Med*. 2007;1:114–119.
24. Riascos R, et al. Imaging of atlanto-occipital and atlantoaxial traumatic injuries: what the radiologist needs to know. *Radiographics*. 2015;35:2121–2134.
25. Gargas J, et al. An analysis of cervical spine magnetic resonance imaging findings after normal computed tomographic imaging findings in pediatric trauma patients: ten-year experience of a level I pediatric trauma center. *J Trauma Acute Care Surg*. 2013;74:1102–1107.
26. Badhiwala JH, et al. The influence of timing of surgical decompression for acute spinal cord injury: a pooled analysis of individual patient data. *Lancet Neurol*. 2021;20:117–126.
27. Singhal V, Aggarwal R. Chapter 11 - spinal shock. In: Prabhakar H, ed. *Complications in Neuroanesthesia*. vols. 89–94. Academic Press; 2016. https://doi.org/10.1016/B978-0-12-804075-1.00011-0.
28. Pearce MS, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet*. 2012;380:499–505.
29. Meulepas JM, et al. Radiation exposure from pediatric CT scans and subsequent cancer risk in The Netherlands. *J Natl Cancer Inst*. 2019;111:256–263.
30. Schneuer FJ, et al. The impact of general anesthesia on child development and school performance: a population-based study. *Pediatric Anesthesia*. 2018;28:528–536.
31. Schulte-Uentrop L, Goepfert MS. Anaesthesia or sedation for MRI in children. *Current Opinion in Anesthesiology*. 2010;23:513–517.

Abbreviations

MRI: magnetic resonance imaging
CT: computed tomography
CST: cervical spinal trauma
CCJ: craniocervical junction