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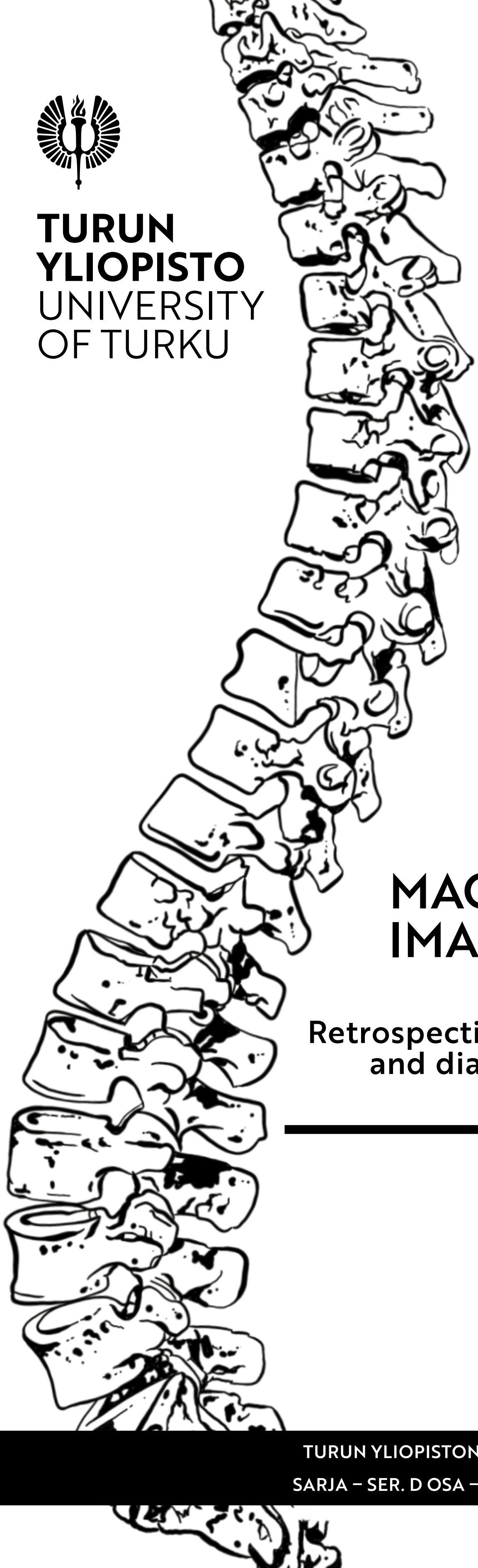

# MAGNETIC RESONANCE IMAGING IN PAEDIATRIC SPINAL TRAUMA

## Retrospective analysis of feasibility, safety, and diagnostic value in the emergency department

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**Aapo Sirén**

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. D OSA – TOM. 1801 | MEDICA – ODONTOLOGICA | TURKU 2024

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*Se on muuten käsittämätön juttu!*

*TKP*

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## ABSTRACT

Paediatric spinal trauma is a relatively uncommon but challenging entity in the emergency department. Despite the algorithms aiming to exclude spinal trauma based on symptoms and physical examination, medical imaging is often needed. Since the early 20th century, conventional radiography has been the most utilised imaging modality. In recent decades, computed tomography (CT) has become a common primary method, accompanied by magnetic resonance imaging (MRI) as an additional imaging in difficult cases and spinal cord injuries. MRI is more sensitive than CT, but it is unclear if MRI yields additional clinical value compared to CT. MRI is also more expensive, time-consuming, and less available than CT. Long scanning time makes sedation or anaesthesia often mandatory with younger children. The goals of this thesis were to assess the feasibility, safety, and accuracy in emergent spinal trauma imaging of children and adolescents.

We retrospectively reviewed the imaging data and medical records of the under-18-year-old patients having undergone spinal MRI at the Emergency Radiology Department of Turku University Hospital 2013–2021 because of acute trauma. MRI demonstrated all injuries requiring surgical treatment. No MRI-related adverse events were reported, and the need for anaesthesia was mainly limited to children aged five years or younger. Unless MRI demonstrated potentially unstable features in spinal injury, the clinical value of follow-up or flexion-extension imaging was low. If the concurrent brain and spine MRI was performed because of a spinal trauma but without symptoms suggesting brain injury, the brain MRI did not reveal any traumatic findings regardless of spinal MRI findings.

Our results show that emergency MRI is an accurate, feasible, and safe imaging modality in paediatric spinal trauma. Spinal injury does not seem to be a risk factor for brain injury if no brain injury-related symptoms are present. Emergency MRI reduces the need for follow-up imaging, but assessing MRI's cost-effectiveness or potential superiority over CT as primary imaging requires further studies.

KEYWORDS: radiology, spine trauma, paediatric, emergency imaging, magnetic resonance imaging, computed tomography, brain injury

TURUN YLIOPISTO
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AAPO SIRÉN: Lasten rankavammojen päivystyksellinen kuvantaminen – takautuva tutkimus magneettikuvauksen käyttökelpoisuudesta, turvallisuudesta ja diagnostisesta merkityksestä
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## TIIVISTELMÄ

Rankavammat ovat moniin lasten ja nuorten vammatyyppeihin verrattuna harvinaisia. Epäilyn herättyä rankavamman luotettava poissulkeminen oireiden ja kliinisten tutkimuslöydösten perusteella on hankalaa, joten rankavammaepäily johtaa usein kuvantamistutkimuksiin. Röntgenkuvausta on käytetty rangan tutkimisessa yli sadan vuoden ajan, mutta viimeisten parinkymmenen vuoden aikana tietokonetomografia (TT) on yleistynyt huomattavasti. Magneettikuvausta (MK) on käytetty täydentävänä tutkimuksena ja erityisesti selkäydinvammaepäilyn yhteydessä. MK osoittaa rangan vammamuutokset herkemmin kuin TT, mutta suuremman herkkyyden merkitys ja hyöty potilaiden hoidossa on toistaiseksi epäselvä. MK on kalliimpi ja hitaampi kuin TT, ja sen saatavuus erityisesti päivystysaikaan on huonompi. Tämän väitöstutkimuksen tarkoituksena oli arvioida MK:n tarkkuutta, turvallisuutta ja toteutettavuutta lasten ja nuorten rankavammaepäilyn vuoksi tehtävänä päivystystutkimuksena.

Tutkimuksessa käytiin takautuvasti läpi Turun yliopistollisen keskussairaalan päivystysradiologian yksikössä vuosina 2013–2021 rankavammaepäilyn vuoksi alle 18-vuotiaille potilaille tehtyjen magneettikuvantamisten tiedot sekä muut vammaan liittyvät potilasasiakirjamerkinnät. MK osoitti kaikki kirurgista hoitoa vaativat rankavammat, eikä kuvantamiseen liittyviä haittatapahtumia ilmennyt. Lähes kaikki yli viisivuotiaat pystyttiin kuvantamaan ilman nukutusta. Jos vammassa ei MK:n perusteella ollut huolestuttavia piirteitä, ei seurantakuvauksista ollut lisähyötyä. Lapsilla, joille tehtiin vamman vuoksi samanaikaisesti rangan ja aivojen MK mutta joilla ei ollut aivovammaan viittaavia oireita, ei magneettikuvaus paljastanut aivovammaa, vaikka rangassa olisikin todettu vamma.

Tulostemme perusteella MK on tarkka ja turvallinen lasten rankavammaepäilyn kuvantamistutkimus. Päivystyksellinen MK vähentää seurantakuvausten tarvetta. Kustannusvaikuttavuuden arviointi kuitenkin vaatii lisätutkimusta, samoin sen selvittäminen, onko MK merkitsevästi parempi kuin TT.

AVAINSANAT: radiologia, rankavammat, lapset ja nuoret, päivystyskuvantaminen, magneettikuvantaminen, tietokonetomografia, aivovamma

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# Abbreviations

| | |
|---|---|
| AARF | Atlantoaxial rotatory fixation |
| AARS | Atlantoaxial rotatory subluxation |
| AI | Artificial intelligence |
| ALARA | As low as reasonably achievable |
| ALL | Anterior longitudinal ligament |
| AX | Axial plane |
| CCJ | Craniocervical junction |
| CCR | Canadian C-spine rule |
| COR | Coronal plane |
| CR | Conventional radiograph (plain radiograph, X-ray) |
| CSF | Cerebrospinal fluid |
| CT | Computed tomography |
| CTA | Computed tomography angiography |
| DTI | Diffusion tensor imaging |
| DWI | Diffusion-weighted imaging |
| ED | Emergency department |
| FE | Flexion-extension |
| FLAIR | Fluid attenuation inversion recovery |
| FOV | Field-of-view |
| FS | Fat-suppression |
| GCS | Glasgow coma scale |
| GRE | Gradient echo sequence |
| MRI | Magnetic resonance imaging |
| mSv | Millisievert |
| MDCT | Multidetector computed tomography |
| NEXUS | National Emergency X-Radiography Utilization Study |
| PACS | Picture archiving and communication system |
| PD | Proton density image |
| PECARN | Pediatric Emergency Care Applied Research Network |
| PLC | Posterior ligamentous complex |
| PLL | Posterior longitudinal ligament |

| | |
|---|---|
| RIS | Radiology information system |
| SAG | Sagittal plane |
| SCIWORA | Spinal cord injury without radiographic abnormality |
| SD | Standard deviation |
| STIR | Short tau inversion recovery |
| SWI | Susceptibility-weighted imaging |
| T1W | T1-weighted image |
| T2W | T2-weighted image |
| T2*W | T2*-weighted image |
| TBI | Traumatic brain injury |
| TE | Time to echo |
| TR | Repetition time |
| UV | Uncovertebral |
| ZTE | Zero echo time |

# List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Sirén A, Nyman M, Syvänen J, Mattila K, Hirvonen J. Clinical outcome following magnetic resonance imaging as first-line imaging in low-impact pediatric spine trauma: a single-center retrospective observational study. *Pediatric Radiology*, 2023; 53: 2269–2280.

II Sirén A, Syvänen J, Nyman M, Mattila K, Hirvonen J. Outcomes of follow-up imaging after pediatric spinal trauma confirmed with magnetic resonance imaging. *Journal of Pediatric Orthopaedics*, 2024; 44(4): 329–334.

III Sirén A, Nyman M, Syvänen J, Mattila K, Hirvonen J. Utility of brain imaging in pediatric patients with a suspected accidental spinal injury but no brain injury-related symptoms. *Child's Nervous System*, 2024; 40: 1435–1441.

IV Sirén A, Nyman M, Syvänen J, Mattila K, Hirvonen J. Imaging outcomes of MRI after CT in pediatric spinal trauma – a single center experience. *Journal of Pediatric Orthopaedics*, 2024; ():10.1097/BPO.0000000000002765. Published online ahead-of-print.

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# 1 Introduction

Paediatric spinal injuries leading to hospitalisation, morbidity or mortality are rare. The incidence is estimated to be 1 per 15 000 children in Finland (Puisto et al., 2010). Emergency department visits because of traumatic injuries among children and adolescents are increasing (L. K. Lee et al., 2022), as well as the use of emergency imaging (Marin et al., 2020). Luckily, the incidence of severe injuries is, however, decreasing (Piatt & Imperato, 2018). Despite its low incidence, serious spinal injury is a dreaded entity because of its devastating consequences, paralysis, or death at worst (Ahuja et al., 2017). Spinal trauma is difficult to exclude based on symptoms and physical examination only. Hence, the contemporary decision-making rules to assess whether the imaging is needed offer low specificity but high sensitivity. To avoid any missed injuries, this leads to a high demand for emergent imaging among children with a suspicion of spinal trauma (Slaar et al., 2017; Luehmann et al., 2020) (Phillips et al., 2021; Sires et al., 2022).

Conventional radiographs (CR) and computed tomography (CT) are recommended as a primary imaging modality, and magnetic resonance imaging (MRI) as complementary imaging if CR or CT is unequivocal regarding a ligamentous injury or spinal cord injury is suspected (The Royal College of Radiologists 2014; Kadom et al., 2019; McAllister et al., 2019). MRI is more sensitive and specific in ligamentous and soft tissue injuries (Schoenfeld et al., 2010) and comparable to CT in osseous injuries (M. Henry, Riesenburger, et al., 2013). Overall, MRI is highly accurate in demonstrating unstable cervical spine injuries in children and adolescents (R. P. Lee et al., 2022). Still, the studies assessing the additional clinical value of MRI over CT have provided mixed results (Schoenfeld et al., 2010; Qualls et al., 2015; Derderian et al., 2019; Al-Sarheed et al., 2020). In addition to the high sensitivity in spinal cord injuries and ligamentous injuries, the lack of ionising radiation exposure is considered a major advantage of MRI, while in CR and CT, ionising radiation exposure is an inherited feature. On the contrary, MRI is more expensive, less available, and more time-consuming. The long acquisition time leads to the need for sedation or anaesthesia, especially in young children.

MRI as a primary or sole imaging modality in paediatric spinal trauma has not been studied before. This thesis aims to retrospectively examine if MRI can be used as a first-line imaging modality in paediatric spinal trauma. We also studied if the high accuracy of MRI can be used to decrease the need for complementary and follow-up imaging, and if head imaging is needed in paediatric spinal trauma patients without suspicion of brain injury.

# 2 Review of the Literature

## 2.1 A brief technical overview of the medical imaging modalities relevant to this thesis

### 2.1.1 Conventional radiographs

Conventional radiography (CR, *radiography, plain radiography, X-ray imaging*) utilises ionising electromagnetic radiation called X-rays (sometimes *Röntgen radiation*). Depending on the structure and tissue density of the imaged body part, the X-rays are absorbed respectively in different parts of the scanned object, contrasting the image (Klein et al., 2018).

X-rays are generated in an X-ray tube, where a high-voltage current accelerates electrons from the cathode to the anode. The interaction of the anode and the accelerated electrons generates the X-rays (Zink, 1997).

The direction and size of the primary X-ray beam exiting the tube are directed with a light beam diaphragm (*beam collimation*). Grids and filters are used between the X-ray tube and the patient to reduce scattering radiation and to remove unnecessary low energy ends from the X-ray spectrum (Forster, 1985). Light beam diaphragm, grids, and filters not only enhance image quality but also contribute to minimising radiation exposure.

The X-ray beam reaches the patient after being modified with collimators, grids, and filters. Photons of the beam are partly absorbed in the patient, depending on the thickness and absorption characteristics of different tissues in the imaged body part. For example, the cortical bone absorbs more photons than fluid, the fluid absorbs more photons than fat, and the air absorbs hardly any photons. Irrespective of the tissue quality, a greater amount of one tissue absorbs more photons than a smaller amount of the same tissue (Samei & Peck, 2019).

The photons not absorbed pass through the patient, reaching the next part of the equipment, the image receptor (*detector*). Traditionally, the detectors were photographic plates or films, but nowadays, the detectors are almost invariably digital. The detector absorbs and registers the photon attenuation of the remaining X-ray beam (Cowen et al., 2008). The information the detector gathers is then digitally processed with an integrated computer and converted into the final two-dimensional image (Samei & Peck, 2019). The final images are stored in the Picture Archive and Communication System (PACS) for archiving and to be reviewed by physicians and radiologists.

The five basic parameters used to optimise image quality and patients' radiation dose include tube voltage (measured in kV), tube current time product (mAs), additional beam filtration (usually copper- or aluminium filters), anti-scatter methods (usually grids), and source-to detector distance (most often 100 cm). Although modern radiography systems have many automated functions and digital image processing is far more forgiving than analogue equipment, the radiographer's craftmanship is crucial in upholding high-quality radiography practice (Samei & Peck, 2019; Steffensen et al., 2021).

### 2.1.2 Computed tomography

Computed tomography (in this thesis, particularly multidetector CT, MDCT) utilises the same principles as CR: The X-ray beam is generated with the X-ray tube, the beam is modified with collimators, grids and filters, and the photons not absorbed in the patient reach the detector. In CT, the X-ray tube and a row of detectors are placed on the opposite sides of a donut-shaped gantry. The patient is placed on the table inside the gantry, and the table is moved through the gantry during the scan. Simultaneously, the tube and the detectors rapidly rotate around the patient within the gantry, constantly facing each other on the opposite sides of the device. The rotational movement of the X-ray tube and the detectors allow attenuation measurements in countless angles, eliminating the structure superimposition seen in CR (Klein et al., 2018).

The attenuation data registered by the detectors is then processed and reconstructed with a computer into a final image data, which is again stored in the PACS. Although the CT technique is based on two-dimensional data acquisition, with modern MDCT scanners and reconstruction methods, the data is collected and processed in an isotropic, voxel-like form. So-called slice thickness or voxel size, i.e. the spatial resolution of the contemporary MDCT scanners, is 0.5-0.625 mm. The final, processed imaging data is often examined in axial, coronal, and sagittal planes. Still, the isotropic acquisition allows the data to be studied in completely freely adjusted planes regardless of the X-, Y-, and Z-axis (Klein et al., 2018; Samei & Peck, 2019).

In addition to the image review independent of the traditional imaging planes or projections, CT allows good contrast resolution with the possibility of scaling the image according to the characteristics of different tissues. This can be done at the radiological workstation by adjusting the *level* and the *width* of the *window* on which the imaging data is scaled. This *windowing* enables precise assessment of the tissues with different radiographic densities, like lung, brain, and bone (Klein et al., 2018) (Samei & Peck, 2019).

### 2.1.3 Magnetic resonance imaging

From the patient's perspective, the modern MRI scanner used in diagnostic imaging looks somewhat like a CT. Still, the equivalent of the CT's gantry is longer, and the patient is positioned inside the scanner. The patient is not moved during the acquisition. Contrary to the CR and CT, magnetic resonance imaging (MRI) does not utilise ionising radiation. It is based on using strong magnetic fields and low-frequency radio waves, which interact with the protons (practically the hydrogen nuclei) in the tissue. More specifically, the MRI system affects and registers the proton's *spin*, the intrinsic momentum of the proton (Samei & Peck, 2019).

The scanner maintains a strong and constant magnetic field with superconducting electromagnets. This constant magnetic field affects everything within the field, making the normally randomly distributed spins of the protons within the tissue line up more uniformly. This net magnetisation (*bulk magnetisation, equilibrium state*) enables the scanner to temporarily interfere with the protons' spins and observe how the spins return to the equilibrium state. These *relaxation* characteristics differ from tissue to tissue. Hence, the information collected from the relaxation processes can be converted to an image with complicated mathematical models. The interference, or *excitation* of the spins, and recording the relaxation process are performed with *coils*. The most important coils include *gradient coils* and *transmit and/or receiver coils.* In general, the gradient coils are needed to acquire spatial information, and the transmit/receiver coils to acquire information, or *signal*, on the internal tissue composition. Both excitation and relaxation data acquisition can be done in many ways. In clinical work, these different ways to gather data and process the data into images demonstrating certain tissue characteristics are called MRI *sequences* (Hashemi, 2018; Samei & Peck, 2019) A very simplified schematic illustration of the proton spin momentum is demonstrated in Figure 1.

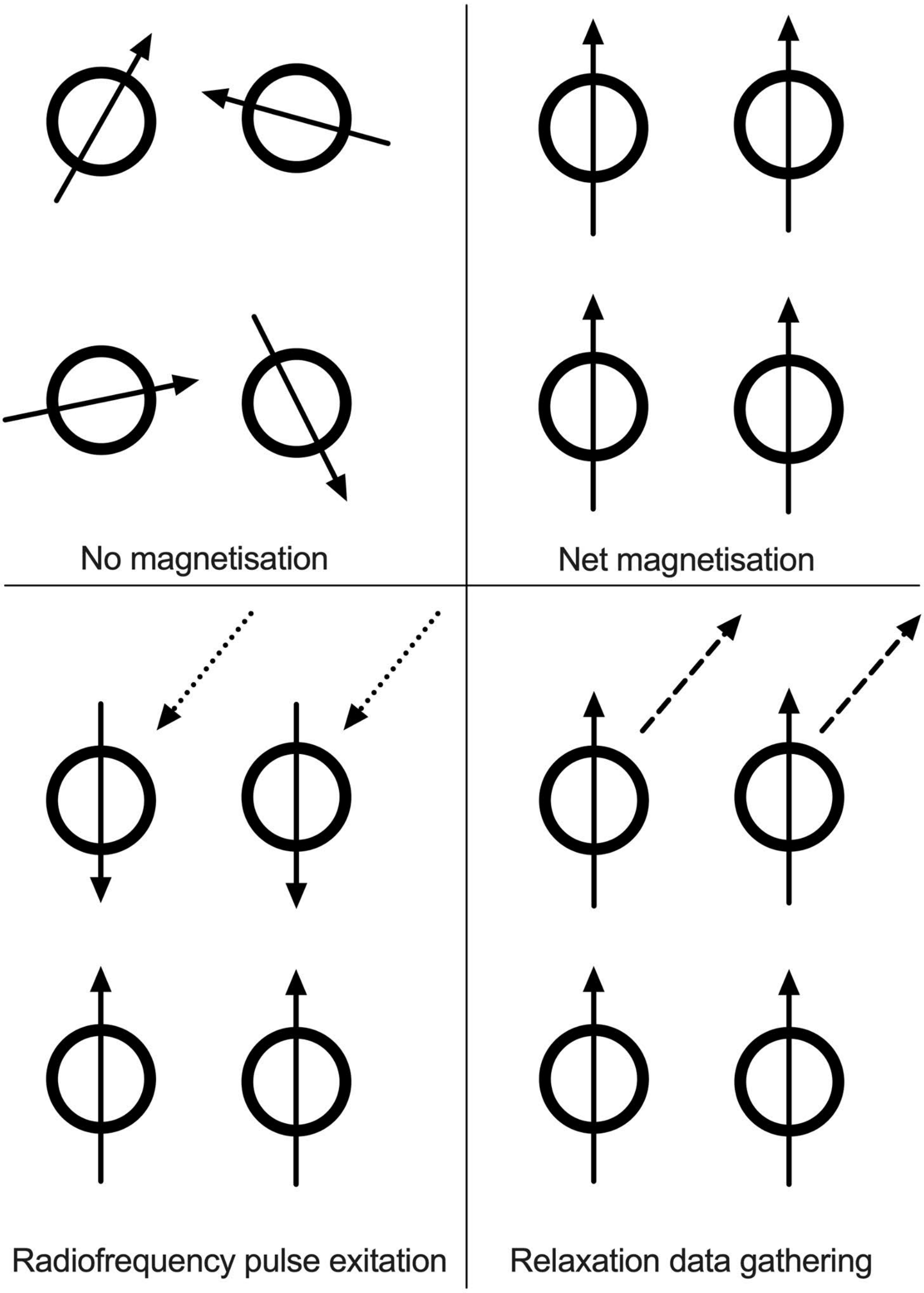

**Figure 1.** A simplified illustration of protons spins with random distribution (no magnetisation), with uniform distribution (net magnetisation), excitated with the radiofrequency pulse, and in the relaxation process when, the relaxation characteristics are recorded.

The most important characteristics measured are T1- and T2-relaxation times, which measure different forms of spin relaxation and proton density (PD), which measures the number of protons within an inspected volume. The sequences based on measuring T1- or T2 relaxation times and PD provide basic information from most tissues of the human body. Still, numerous derivatives of these basic sequences have been developed to increase the sensitivity and specificity of MRI and expand its applications. Regarding spinal trauma imaging, the most important addition to the traditional T1- and T2-weighted sequences (T1W and T2W) are the pulse sequence-based methods to *saturate* or *suppress* the signal of fat. Fat yields a lot of signal in both T1W and T2W, i.e., the tissue with a high fat concentration is presented as whitish or *bright* in the final image. In T2W, water is bright too, and, in addition to the spaces containing only water, the more heterogenous tissue oedema seen in many pathological processes, including trauma, is bright in T2W. If the signal from the fat is nulled, the oedema remains bright and is readily distinguished. In T1W, water yields only a little signal, i.e., water and oedema are dark in the final T1W image. Therefore, pure T1W has a limited utility in depicting soft tissue oedema, whether fat saturation is used. However, osseus oedema can be seen in T1W. In addition to fat-saturated (FS) T2W, an effective sequence named short tau inversion recovery (STIR) is used in spinal trauma imaging, which often provides better image quality than FS T2W. It is also a fine example of the obvious complexity of the physical and mathematical background of MRI imaging. Despite often being considered a more reliable version of fat-saturated T2-weighted imaging in the radiologist's clinical work, technically speaking, it seems not to be a proper fat saturation technique (it saturates tissue with T1-values in the range of fat), nor is it a T2-weighted image, but yields both T1- and T2-weighted image contrast (Hashemi, 2018; Samei & Peck, 2019).

Numerous more specific MRI sequences exist, the following exemplary list being far from comprehensive: Sequences optimised for observing blood include T2*-weighted imaging (T2*W) and the susceptibility weighted imaging (SWI). Diffusion weighted imaging (DWI), which demonstrates the diffusivity of water molecules within a tissue, and its derivative diffusion tensor imaging (DTI) which is used to assess the anatomy and integrity of certain specific tissues, most often the organisation and integrity of neuronal axons in central nervous system. A pulse sequence called fluid attenuated inversion recovery (FLAIR) is routinely used in brain imaging to null the signal from the cerebrospinal fluid. Time-of-flight (TOF) sequence demonstrates the arterial or venous flow without administration of contrast agent. A gadolinium-based contrast agent can be used intravenously to increase tissue contrast. It can be used in vascular imaging, but more often in diagnostic workup of tumours, infections, and inflammations. Perfusion-weighted imaging can visualise and measure dynamic blood flow in a volume of tissue (Hashemi, 2018; Klein et al., 2018; Samei & Peck, 2019).

In addition to extending and improving the diagnostic abilities of MRI, the constant development of techniques to make MRI more achievable and applicable to patients in need is ongoing. For example, recently commercialised artificial intelligence (AI) -based image processing methods have provided improvements, allowing better image quality with less data. These AI tools can be used either to scan the patients faster without sacrificing the diagnostic quality or to keep the scanning time constant while improving the image quality (Singh et al., 2023).

## 2.2 Overview of paediatric spinal trauma from the radiologist's perspective

### 2.2.1 Epidemiology of paediatric spinal trauma

Children are prone to injuries. Paediatric emergency department (ED) visits because of traumatic injury are increasing, even if hospitalisations and deaths are not on the rise (L. K. Lee et al., 2022). The imaging of paediatric patients is also increasing in the EDs (Marin et al., 2020). Pediatric spinal trauma is rare, but the exact incidence is unknown (Platzer et al., 2007; Shin et al., 2016; Saul & Dresing, 2018; Compagnon et al., 2020). In a Finnish registry-based study, the annual incidence of paediatric spinal trauma requiring hospitalisation was 1 per 15,000 children (Puisto et al., 2010). The incidence of traumatic spinal cord injury is much smaller, with the estimated incidence being 4.3 per 1 million in developed countries (Jazayeri et al., 2023). The incidence of paediatric spinal injuries requiring hospitalisation or leading to death has declined, in contrast to the increasing number of emergency department visits (Piatt & Imperato, 2018).

Paediatric traumatic brain injury (TBI) is more prevalent than spinal trauma, the annual incidence being between 47 and 280 per 100,000 children, depending on the country (Dewan et al., 2016). Suspected TBI is a common cause of ED visits in the paediatric population (Al Mukhtar et al., 2022), and both the number of ED visits because of suspected TBI (Hanson et al., 2019) and confirmed mild TBI are increasing (Kuitunen et al., 2023).

### 2.2.2 General characteristics of the paediatric spinal trauma

The lax ligaments, incomplete ossification and relatively big head predispose children younger than 7–9 years of age to ligamentous injuries of the craniocervical junction (CCJ). Later on, the injury profile becomes more comparable to that of adults – more injuries of the subaxial cervical spine and fewer in the CCJ (Mohseni et al., 2011; J. R. Leonard et al., 2014).

Children often have traumatic findings on more than one spinal level. Multi-level injuries are present in 27–49% and non-contiguous injuries in 6–12% of all paediatric spinal injuries (Saul & Dresing, 2018; Compagnon et al., 2020).

### 2.2.3 Emergent diagnostic workup of paediatric spinal trauma

Despite the fortunate sparseness of paediatric spinal trauma leading to disability or death, suspected blunt spinal trauma is a common cause of ED visits among children and adolescents. With every individual patient, the responsible ED physician must consider whether medical imaging is needed. The known injury mechanism and the forces involved in the injury usually guide the basic approach of the diagnostic strategy. Patients with high-energy trauma, like pedestrians struck by a car, a motor vehicle accident with a speed of at least 60 km/h or fall from a height of 2 meters or more, are assessed according to the standardised trauma protocol, including computed tomography (CT) of the cervical and thoracolumbar spine (The Royal College of Radiologists, 2014; Madura & Johnston, 2017).

Most paediatric patients with suspected spinal trauma do not belong to this group with high-energy trauma. Therefore, the need for imaging must be assessed individually based on patient history, injury mechanism and clinical findings. This is not an easy task because significant injuries are rare but can lead to permanent neurologic deficits or death if left untreated (J. R. Leonard et al., 2014). Regarding the cervical spine, clinical decision-making rules developed for adult trauma patients, especially the Canadian C-spine rule (CCR) (Stiell et al., 2001) and the National Emergency X-Radiography Utilization Study (NEXUS) (Hoffmann et al., 1998) criteria, have been applied to paediatric patients. The Pediatric Emergency Care Applied Research Network (PECARN) has developed clinical decision-making criteria for paediatric patients (J. C. Leonard et al., 2011). These rules are sensitive, but even the PECARN criteria do not offer the specificity that would be needed to reduce the need for imaging significantly (Slaar et al., 2017; Luehmann et al., 2020; Phillips et al., 2021; Sires et al., 2022). No clinical decision-making rules exist for the suspected paediatric thoracolumbar injury. Overall, medical imaging is often needed in suspected paediatric spinal trauma.

### 2.2.4 Imaging approach in paediatric spinal trauma

The most appropriate emergent imaging modality in paediatric spinal trauma always depends on the patient, injury mechanism and local resources. Trade-offs must always be made in choosing the imaging method.

#### 2.2.4.1 Conventional radiographs

Conventional radiographs (CR) and CT are widely recommended as the primary imaging modality for suspected paediatric spinal trauma, and the role of MRI has been in further evaluating patients with neurological symptoms (Kadom et al., 2019; McAllister et al., 2019). The major advantages of CR include wide availability, fast acquisition time, and low costs. In the cervical spine, CR with frontal and lateral projections is shown to yield good accuracy for unstable spinal injuries (Nigrovic et al., 2012; Cui et al., 2016; Arbuthnot & Mooney, 2017). However, CR interpretation is not always straightforward (Avellino et al., 2005).

#### 2.2.4.2 Computed tomography

In the adult population, CT outperforms CR in cervical spine injuries, especially with high-risk patients (Holmes & Akkinepalli, 2005). Among children, the studies comparing CR and CT have mixed results. Two studies did not find CT useful in addition to CR (Adelgais et al., 2004; Chupik et al., 2004). Still, a newer study with a larger sample (Hale et al., 2017) suggested that CT should be used instead of CR in the clearing of the paediatric cervical spine. Nowadays, CT is also usually available in hospitals that provide emergency care. CT is also relatively fast to perform, although sedation might still be needed with younger and restless children to obtain sufficient image quality. The cost per scan is higher than in CR but lower than in MRI. Radiation exposure of CT is higher compared to CR.

#### 2.2.4.3 Magnetic resonance imaging

CR and MRI were compared by Moore et. al (Moore et al., 2017), who concluded that using CR might not be justified in the diagnostic workup of paediatric spinal trauma because of its low negative predictive value. More studies comparing CT and MRI are available. MRI is comparable to CT in detecting significant paediatric spinal injuries (M. Henry, Riesenburger, et al., 2013; Gargas et al., 2013; M. Henry, Scarlata, et al., 2013; R. P. Lee et al., 2022) and more sensitive than CT, especially in obtunded children (Schoenfeld et al., 2010; Al-Sarheed et al., 2020). The safety profile of emergency spinal MRI is excellent (R. P. Lee et al., 2022). However, it is uncertain if MRI provides additional diagnostic value over CT (Qualls et al., 2015;

Derderian et al., 2019; Franklin et al., 2019; Stephenson et al., 2023) regarding unstable injuries. According to estimations by Frank et al. (Frank et al., 2002), it is possible that despite its higher cost per scan, MRI might help to reduce overall costs in the treatment of obtunded paediatric patients with suspected spinal trauma. MRI is always needed in the presence of neurological symptoms or findings, as it is the only imaging modality showing the spinal cord and nerve root injuries (McAllister et al., 2019). In paediatric trauma patients, a rare entity known as spinal cord injury without radiographic abnormality (SCIWORA) can be found (Pang & Wilberger, 1982; Pang, 2004). MRI is the only imaging modality showing cord injury in SCIWORA. However, there seems to be a small number of patients with neurological symptoms suggesting spinal cord injury but no traumatic findings in contemporary MR imaging, sometimes referred as spinal cord injury without neuroimaging abnormality, SCIWONA.

The drawbacks of MRI include lower availability, longer scanning times, and higher cost per scan. Longer scanning times also lead to the need for anaesthesia when scanning younger and restless children, further increasing the costs and the need for resources. Still, MRI is free of ionising radiation, unlike CR and CT.

## 2.3 Ionising radiation in medical imaging

Medical imaging using ionising radiation is thought to be associated with increased future cancer risk (Brenner et al., 2001; Amis et al., 2007; Smith-Bindman et al., 2009; Sodickson et al., 2009), especially in the paediatric population (Miglioretti et al., 2013; Banerjee & Thomas, 2019). Still, the association and causality has been questioned (Goldman, 1996; Sacks et al., 2016), particularly because the biological basis of the theory is established with high-dose radiation (doses more than 100 mSv), especially with atomic bomb survivors (Preston et al., 2007). Also, the methodology of certain large epidemiological studies suggesting the increased cancer risk due to radiation exposure in medical imaging has been criticised (Boice, 2015), and it has been expressed that the causality between low-dose radiation and increased cancer risk is still to be confirmed (Siegel, Pennington, et al., 2017). A recent multinational large-scale retrospective study strived to overcome the deficiencies of the earlier epidemiological studies (Bosch De Basea Gomez et al., 2023). They found a small but quantifiable increased risk of hematologic malignancies in patients who had undergone CT as a child. Even if this would be considered as a conclusive result, the increased risk of solid cancer after low-dose radiation exposure seems to remain uncertain.

Currently, most organisations working with radiation protection advise reducing ionising radiation exposure as much as possible, partly due to the precautionary principle (ICRP, 2007), especially in the paediatric population (Frush & Goske, 2015). Modern CT scanners and advanced image reconstruction techniques, like deep-learning-based image reconstruction, can help to lower the doses when CT is needed (Nagayama et al., 2018; Gottumukkala et al., 2019) and to follow the fundamental principle of radiation protection – As Low As Reasonably Possible (ALARA). However, the dose reduction and evasion of CT imaging must not happen at the cost of prompt diagnostics (Siegel, Sacks, et al., 2017).

Regarding radiation protection, MRI is a worry-free imaging modality. It does not expose the patient to ionising radiation.

## 2.4 The patient safety and the need for sedation or anaesthesia in medical imaging

### 2.4.1 Safety aspects and the need for anaesthesia in conventional radiographs and computed tomography

It takes only a couple of seconds to scan one CR projection. Excluding some patients with neurological or developmental disorders challenging the cooperation or the ability to stay still, the requested CR series can be obtained fully awake, even in the paediatric population. With CT, the whole imaging procedure takes 2–5 minutes, and the most critical phase requiring complete motionlessness usually lasts 5–90 seconds, depending on the scanner, scanning protocol and the scanned body part. Light sedation or anaesthesia with intubation is sometimes needed with younger and restless children, but usually sufficient image quality is achieved awake.

In general, CR or CT procedures do not bear immediate risks to patient safety. Contrast media use and its risks are not described here because contrast media is not routinely used in primary spinal trauma imaging. Potential risks related to ionising radiation are acknowledged above.

### 2.4.2 Safety aspects and the need for anaesthesia in magnetic resonance imaging

#### 2.4.2.1 Patient safety in magnetic resonance imaging

MRI is much more time-consuming than CR or CT and bears safety risks related to using a strong magnetic field. Safety requirements should be assessed case by case before the patient arrives at the MRI unit, and they must be secured again before bringing the patient to the actual scanner room. All medical and non-medical foreign bodies, implants, devices, tubes, catheters, clothes, etc., must be acknowledged, and their MRI compatibility must be assessed. MRI produces heat in the matter within the magnetic field. Therefore, the patient's body temperature must not exceed the safety limits (usually no more than 38°C). (ACR Committee on MR Safety, 2020; MHRA, 2021). However, a study by Lo et al. suggests (Lo et al., 2014) that the core body temperature of anaesthetised children does not significantly increase during the MRI. Still, on the contrary, they pointed out the risk of hypothermia, which the anaesthesiologist must bear in mind. Overall, MRI-related adverse effects are very rare in the paediatric population, with the reported incidence in different studies being 0.37%–0.62% (Jaimes et al., 2018; Snyder et al., 2018; R. P. Lee et al., 2022).

#### 2.4.2.2 The need for anaesthesia in magnetic resonance imaging

Currently, the MRI procedure takes approximately 20 minutes with a fully cooperative patient and a limited number of sequences. During the image acquisition, the patient must stay still. Otherwise, motion artefacts will occur in the images. One MRI sequence usually takes 45–400 seconds to obtain, and in imaging the paediatric spine, the usual protocol includes 5–8 sequences. Therefore, the MRI protocol usually lasts at least 10–15 minutes, even with contemporary deep-learning-based methods (Singh et al., 2023) and other technical innovations that help speed up image acquisition. However, a fast protocol for paediatric spinal MRI with sufficient diagnostic image quality has been described by Spampinato et al. (Spampinato et al., 2023). With their protocol, total scan time was less than 6 minutes for a toddler and less than eight minutes for a teenager over 6 feet tall.

Because of the anxiety and long acquisition time, MRI often requires light sedation or anaesthesia with intubation with younger, restless, and critically ill children. However, the need for sedation can be diminished with the help of parents, friendly and dedicated staff, interactive mobile phone applications, toy scanners, and a multimedia environment in the scanning room (Runge et al., 2018; Thestrup et al., 2023). The interactive applications or toy scanners are usually not applicable in emergency circumstances. Still, the fundamental methods of working with paediatric patients, like patience, flexibility, and containment of emotions, are also useful in the setting of acute trauma (Lerwick, 2016). Even with children having mild TBI, a behavioural-play familiarisation procedure has been shown to decrease the need for sedation in the emergency MRI (Dégeilh et al., 2023). Limiting the use of anaesthesia is important not only resource-wise but also to avoid the immediate risks of anaesthesia (Cauldwell, 2011) and long-term adverse effects of anaesthetics and sedatives (Andropoulos, 2018; Feng et al., 2020).

## 2.5 Imaging protocols in magnetic resonance imaging of paediatric spinal trauma

Pediatric spinal MRI is performed utilising the same sequences as with grown-up patients. T1-weighted (T1W) and T2-weighted (T2W) images are used to assess anatomy, epidural and intradural hematomas, and especially T1W for fractures. Fat-suppressed (FS) imaging is crucial to detect oedema in bone, soft tissue, ligaments, and spinal cord. FS T2W images can be used, but the short tau inversion recovery (STIR) sequence provides more uniform fat suppression and, therefore, better image quality. Usually, the standard protocol includes sagittal T1W, sagittal and axial T2W and coronal or sagittal FS T2W or STIR (Kumar & Hayashi, 2016) (Benedetti et al., 2000). The ligaments of the CCJ are best seen in dedicated small field-of-view imaging with proton density (PD) and T2W imaging, thin slice thickness (3 mm at maximum) and high field strength (1.5 tesla at minimum) (Nidecker & Shen, 2016).

For spinal cord imaging, T2W is the cornerstone, followed by T1W (Chandra et al., 2012). T2*-weighted gradient echo sequence (T2*W GRE) or susceptibility-weighted imaging (SWI) helps to distinguish even minor cord haemorrhages, although they are challenging to obtain because of sensitivity to pulsation artefacts and motion artefacts (Wang et al., 2011; Haller et al., 2021). Diffusion-weighted imaging (DWI) and diffusion tensor imaging (DTI) have been studied in cord imaging. They might help detect subtle spinal cord injuries and serve as a prognostic marker. Still, their role in clinical practice is yet to be established (Shen et al., 2007; Yin et al., 2010; Pouw et al., 2012; Talbott et al., 2019; Shanmuganathan et al., 2020).

## 2.6 Injury types, emergency MRI findings, and pitfalls in paediatric spinal trauma imaging

Overall, the injuries seen in the paediatric spine are not very different from the spinal injuries in adults. However, the occurrence of some injury types differs (Mohseni et al., 2011; J. R. Leonard et al., 2014). Some pitfalls in spinal imaging are unique to children of a certain age group. The injury types, physiological imaging findings and artefacts described in this paragraph are seen in Table 1.

**Table 1.** Injury types, physiological findings and imaging artefacts discussed below.

| FRACTURES | LIGAMENTOUS INJURIES | SPINAL CORD INJURIES | OTHER INJURIES | PITFALLS |
|---|---|---|---|---|
| Bone bruises | Craniocervical ligaments | Spinal cord transection | Intervertebral disc injury | Cervical pseudosubluxation |
| Simple compressions | Posterior ligamentous complex | Spinal cord contusion | Muscle injury | Vertebral wedging |
| Burst fractures | Anterior longitudinal ligament | SCIWORA | Nerve plexus injury | Juvenile spondylolysis |
| Chance fractures | Posterior longitudinal ligament |  | Vascular injury | Normal appearance of skeletal maturation |
| Avulsion fractures |  |  |  | Pulsation artefacts |
| Posterior arch fractures |  |  |  | Motion artefacts |
|  |  |  |  | Metal-induced artefacts |

## 2.6.1 Fractures

MRI has a high negative predictive value in spinal fractures, fat-suppressed sequences, particularly STIR, being very sensitive in trauma (M. Henry, Scarlata, et al., 2013; Kumar & Hayashi, 2016). T1- and T2-weighted sequences are used to assess the fracture morphology further. When more detailed visibility on structural osseous anatomy is needed, the novel sequences with high spatial resolution are useful and can be used instead of complementary CT. Currently, the most applicable are the zero echo time (ZTE) sequences (Aydıngöz et al., 2022; Wiesinger & Ho, 2022). Of all paediatric patients suffering of spinal fractures, 27–49% have fractures at more than one level (Saul & Dresing, 2018; Compagnon et al., 2020).

### 2.6.1.1 Compression fractures

Compression fractures can occur in any spinal level. Of all paediatric patients having a compression fracture, over 80% have fractures in more than one vertebra (Junewick et al., 2014; Franklin et al., 2019. Paediatric compression fractures are often at a non-junctional level (Franklin et al., 2019). MRI displays compression fractures and vertebral bone contusions without visible structural height loss (Qaiyum et al., 2001), Figure 2.

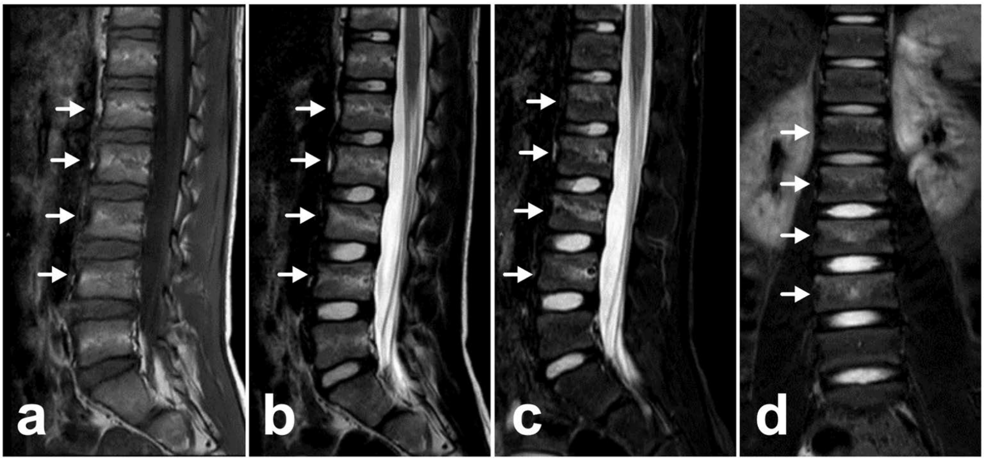

**Figure 2.** Minor compression fractures from L1 to L4 on a 13-year-old patient after a trampoline accident. **a** Sagittal T1-weighted. **b** Sagittal T2-weighted. **c** Sagittal short tau inversion recovery. **d** Coronal short tau inversion recovery. Images retrieved without identifiers from the PACS of Turku University Hospital.

#### 2.6.1.2 Burst fractures

Like simple compression fractures, burst fractures are inflicted by an axial load to the vertebral body, but burst fractures are related to traumas with higher energy. Burst fractures include disruption of one or both vertebral endplates and the posterior cortex of the vertebral body, usually resulting to widening of the interpedicular distance. Retropulsion of the dorsal fragments is traditionally considered to be the pathognomonic part of the burst fracture (Holdsworth 1970; Denis et al., 1984; Atlas et al., 1986). However, widely used AO Spine classification (Vaccaro et. al., 2005) does not define the retropulsion of the fragments as a definitive feature of the burst fracture if endplate and dorsal cortex are fractured. In the paediatric population, burst fractures are uncommon. Burst fractures of the thoracic spine bear a higher risk to the neurologic deficit compared to the lumbar spine (Vander Have et al., 2009). In addition to the assessment of the fracture morphology, MRI enables an instant assessment of the potential spinal cord injuries, hematomas of the spinal canal and concurrent ligamentous disruptions.

#### 2.6.1.3 Chance fractures

Chance fractures are rare in the paediatric population. They are high-energy injuries often caused by motor vehicle accidents. The most commonly affected levels are L2 and L3 (Arkader et al., 2011). CT is usually first-line imaging with these patients with high-energy trauma. As secondary imaging, MRI demonstrates physeal and discal involvement, ligamentous injuries, and spinal cord injuries in addition to fractures (Groves et al., 2005; de Gauzy et al., 2007; Arkader et al., 2011; Le et al., 2011).

#### 2.6.1.4 Avulsion fractures

Most avulsion fractures of the paediatric spine are avulsions of craniocervical junction ligaments. The most common is the avulsion of the alar ligament. It may avulse from its origo in the occipital condyle or its insertion in the dens axis. MRI demonstrates not only the fracture but the ligamentous tears too (Riascos et al., 2015; Beckmann et al., 2020; Fiester et al., 2021).

Acute clay-shoveler-type avulsions of the spinous process are seen in children and adolescents, most often in teenage athletes. They demonstrate oedema in the spinous process, and the actual avulsion fragment is also seen. (Yamaguchi, Myung, et al., 2012). Chronic spinous process stress fractures (sometimes called apophysitis of the spinous process) may have a similar oedematous MRI appearance to acute fractures, and they are also most common in teenage athletes. However, the symptoms follow a more gradual course than acute fractures. When in doubt, a targeted CT or ZTE MRI of the affected level helps to differentiate an acute, sharp avulsion fracture from chronic injuries with sclerosis and fragmentation (Schmitt & Rücker, 1979; Dellestable & Gaucher, 1998).

#### 2.6.1.5 Other fractures

Many other fractures can occur in the paediatric spine (Mistry et al., 2022). For example, fractures of the vertebral arch (e.g., Jefferson fractures and hangman fractures), spinous process, transverse process, and facet joints can be identified in MRI, the oedema of injured vertebrae being the most sensitive sign of fracture. Any spinal fracture in children indicates significant trauma energy, underlining the importance of careful clearance of the spine and excluding any other traumatic findings.

## 2.6.2 Ligamentous injuries

MRI is superior to other imaging modalities (Benedetti et al., 2000; McAllister et al., 2019) in ligamentous injuries. Ligamentous discontinuity and potential spinal malalignment are most easily assessed on T2-weighted and STIR sequences. The latter demonstrates oedema also in partial tears or strains without visible structural disruption. The threshold for performing MRI should be low, especially in suspected CCJ trauma (Riascos et al., 2015; McAllister et al., 2019).

### 2.6.2.1 Ligaments of the craniocervical junction

The craniocervical junction consists of the occipitocervical and atlantoaxial joints. These joints are mobile structures allowing the flexion-extension and rotation movements of the head. The joints' biomechanics and the importance of different stabilising structures are not yet completely understood. The joint capsules, the alar ligaments, and the transverse ligament are crucial in stabilising the joints (Dickman et al., 1991; Cattrysse et al., 2007; Riascos et al., 2015). The tectorial membrane's role is more controversial, but it might also be of importance in preventing CCJ overextension (Steinmetz et al., 2010; Riascos et al., 2015). Injury to the stabilising structures may lead to instability. Isolated soft tissue injuries and avulsion fractures without complete joint dissociation may also occur. All the joints and ligaments mentioned above are visible on MRI but not on CT. Stephenson et al. (Stephenson et al., 2023) suggested, based on three patients, that a retroclival hematoma might be a promising indicator for a CCJ ligamentous injury in CT, but the frequency of retroclival hematoma in these injuries needs to be confirmed with larger samples. Higher field strength and dedicated proton density (PD)- and T2-weighted sequences with a small field of view help to delineate these small structures better (Nidecker & Shen, 2016).

### 2.6.2.2 Posterior ligamentous complex

The posterior ligamentous complex (PLC) includes ligamentum flavum, interspinous ligament, supraspinous ligament, and facet joint capsules. It is considered a vital structure for spinal stability in the classification systems proposed for spinal trauma (Sethi et al., 2009). Of these classifications, the TLICS (Vaccaro et al., 2005) (Sellin et al., 2016; Dawkins et al., 2018) and AO Spine (Vaccaro et al., 2016; Mo et al., 2019; Mo et al., 2021) systems have been studied in the paediatric population with the results of good interrater reliability.

Regarding MRI and the mentioned classifications, the interrater reliability of the TLICS was found to be lower with patients who had undergone MRI than with those treated based on CT imaging only (Dawkins et al., 2018). However, as the authors discussed, this is probably explained by the MRI's superior sensitivity in demonstrating stable PLC injuries that would not be detected in CT or CR. It is possible that the MRIs suggested poor interrater reliability with the TLICS classification could be improved with education, given that, in the respective study, the spine surgeons with varying experience read the MRIs, and no radiologists were involved in the study. With CT and CR, the review of the PLC is based on indirect measures, e.g. the widened interspinous distance. MRI can differentiate the very components of the PLC, revealing the actual culprit behind the CT and CR findings (Benedetti et al., 2000), Figure 3.

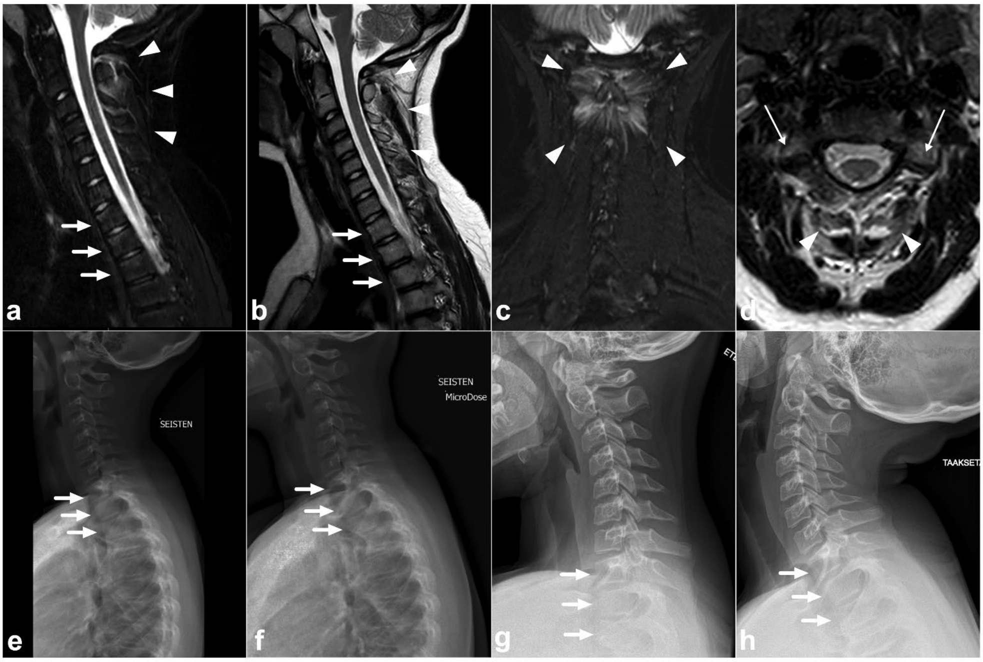

**Figure 3.** 12-year-old boy after a trampoline accident. Emergency MRI revealed oedema suggestive of a partial tear in the posterior atlantooccipital ligament, posterior atlantoaxial ligament, and interspinous ligaments at levels C1-C4 (**a** and **b,** arrowheads). There is also oedema in the deep layer and middle layer muscles of the posterior neck (**c** and **d**, arrowheads). In contrast to likely unstable posterior ligamentous complex disruption, ligamentum flavum is intact, and the facet joint capsules show no signs of injury (**d**, thin arrows). Minor compression fractures were seen on the vertebrae Th1, Th2, and Th3 (thick arrows). The findings remained unchanged in the plain radiograph follow-up imaging, and the flexion-extension plain radiographs were unremarkable. **a** Sagittal short tau inversion recovery. **b** Sagittal T2-weighted. **c** Coronal short tau inversion recovery. **d** Axial T2-weighted. **e** Lateral plain radiograph, 1 day after the injury, the EOS system. **f** Lateral plain radiograph, 2 weeks after the injury, the EOS system. **g-h** Flexion-extension plain radiographs, 4 weeks after the injury. Images retrieved without identifiers from the PACS of Turku University Hospital.

#### 2.6.2.3 Anterior and posterior longitudinal ligaments

Injuries of the anterior and posterior longitudinal ligament (ALL and PLL) can occur as a part of a gross fracture-dislocation. The literature on isolated or non-dislocated ALL and PLL injuries in the paediatric population is scarce. These injuries might be rare, especially in pre-school-aged children, but the overall incidence is unknown (Jacob et al., 2016).

### 2.6.3 Other non-osseous injuries

#### 2.6.3.1 Intervertebral disc injuries

Like any intervertebral disc pathology, acute traumatic injuries of the disc are best seen with MRI (Ghanem et al., 2006). The healthy nucleus pulposus of the disc has physiologically high T2-signal, but oedema related to acute traumatic injury can be separated using FS T2W or STIR sequences. Degenerative intervertebral disc changes are not uncommon in the paediatric population (Paajanen et al., 1997; Kjaer et al., 2005; Lund et al., 2022), and these should not be confused with acute injuries with an oedematous signal.

#### 2.6.3.2 Muscle injuries

MRI is the gold standard in muscle trauma imaging (Flores et al., 2018). Spinal muscle trauma seldom requires specific treatment. Muscle trauma is best appreciated on FS T2W or STIR sequences, where the injury appears as high-signal areas. The hematomas associated with major muscular injuries, as well as Morel-Lavallée-lesions, are also visible on FS T2-weighted and STIR images (Volavc & Rupreht, 2021).

#### 2.6.3.3 Nerve plexus injuries

Definite treatment planning in cervical and sacral nerve plexus injuries requires dedicated imaging (Soldatos et al., 2013; Gilcrease-Garcia et al., 2020). However, with a trauma patient having neurological symptoms in the extremities, the emergency spinal MRI can be extended to immediately confirm or exclude a possible nerve plexus injury, especially with the associated oedema. If the dedicated neurography sequences are unavailable or otherwise unapplicable, routine FS T2W or STIR sequences provide good sensitivity in injury detection (Gilcrease-Garcia et al., 2020).

#### 2.6.3.4 Vascular injuries

Computed tomography angiography (CTA) has been a workhorse in suspected vascular injury imaging for decades (Ofer et al., 2001; Chokshi et al., 2011; So et al., 2022). On a routine cervical spine MRI, an arterial injury can be detected as an abnormal flow void, especially in T2W, but also in T1W, STIR, and PD-sequences (Lévy et al., 1994; Kohler et al., 2011). Vessel wall injury (dissection or intramural hematoma) can also be seen in routine sequences. When in doubt, modern vessel wall imaging techniques with a high spatial and contrast resolution can significantly improve the detection and characterisation of minor vessel wall injuries (Rutman et al., 2018; Nagpal et al., 2018; Vranic et al., 2020). However, vascular injury cannot be excluded with a routine spinal trauma MRI only.

### 2.6.4 Spinal cord injuries

Using MRI in acute spinal cord injury was first described in 1983 by Modic et al. in their two papers: (Modic, Weinstein, Pavlicek, Starnes, Boumphrey & Duchesneau 1983; Modic, Weinstein, Pavlicek, Boumphrey, Starnes, & Duchesneau 1983), and it has been the gold imaging standard in cord injuries ever since. The cord can usually be assessed with T1W, T2W, and FS T2W or STIR sequences. Diffusion-weighted imaging (DWI) and diffusion tensor imaging (DTI) might be useful in detecting subtle injuries. They might also serve as a prognostic biomarker. Still, the role of these techniques in clinical practice is not fully established yet (Shen et al., 2007; Yin et al., 2010; Pouw et al., 2012; Talbott et al., 2019; Shanmuganathan et al., 2020). Susceptibility-weighted imaging (SWI) or T2*-weighted sequences might increase the sensitivity in detecting small intramedullary haemorrhages. However, they are challenging to obtain because of their sensitivity to pulsation artefacts and motion artefacts (Wang et al., 2011; Haller et al., 2021). Usually, the spinal cord injury is seen as an abnormally high signal intensity, sometimes subtle, in T2W or STIR sequences. The other extreme is a complete cord transection (Mendelsohn et al., 1990; Chandra et al., 2012). The BASIC classification system can be used to grade the MRI findings in spinal cord injury (Talbott et al., 2015).

Spinal cord injury without radiographic abnormality (SCIWORA) is almost merely seen in children, although it has been described in adults too (Kim et al., 2004). Pang and Wilberger first described the term SCIWORA in 1982 (Pang & Wilberger, 1982), but symptomatic spinal cord trauma without fracture or dislocation was already recognised earlier (Audic & Maury, 1969). SCIWORA is thought to occur due to the substantial mobility and laxity of the children’s spine, allowing a self-reducing displacement damaging the cord (Pang, 2004). The introduction of MRI and its expanding use in suspected cord injuries has led to a terminological discussion evolving the concept of SCIWORA (Dreizin et al., 2015;

Farrell et al., 2017) by providing visibility to the cord itself and sometimes revealing structural injuries not seen in CR or CT (Gargas et al., 2013). Nevertheless, there seem to be some patients with neurological symptoms from spinal cord injury not perceptible in contemporary MRI, eventually with a favourable long-term clinical outcome (Pang, 2004; Zou et al., 2021).

### 2.6.5 Physiological findings and pitfalls in emergency MRI of paediatric spine

Many practical issues have to be taken into account when interpreting the emergency MRI of the paediatric spine. Some of these are universally related to MRI, but children have some peculiarities that the radiologist and the responsible physician must be aware of. It is important to separate physiological findings and artefacts from traumatic injuries.

#### 2.6.5.1 Pseudosubluxation of the cervical spine

Pseudosubluxation in the subaxial cervical spine is a normal variant in younger children and it is thought to disappear until the age of ten years. It is essential to distinguish pseudosubluxation from true subluxation. Pseudosubluxation is most commonly seen in level C2/3, followed by level C3/4 (Cattell & Filtzer, 1965; Swischuk, 1977; Shaw et al., 1999; O'Neill et al., 2021). On MRI, the lack of osseous or soft tissue oedema in addition to the normal posterior cervical line (Swischuk line) makes the recognition of pseudosubluxation more straightforward and reliable than with CR or CT.

#### 2.6.5.2 Vertebral wedging

Anterior wedging of the vertebral bodies is a normal physiological phenomenon. Wedging disappears gradually with skeletal maturation (Swischuk et al., 1993; Gaca et al., 2010; Canadian STOPP Consortium National Pediatric Bone Health Working Group, 2015). With MRI, physiological wedging is readily distinguished from acute compression fractures by the absence of bone marrow oedema or fracture line.

#### 2.6.5.3 Juvenile spondylolysis

Juvenile lumbar spondylolysis ensues from repetitive stress, but the onset of symptoms can be sudden, or the chronic pain may be exaggerated by acute trauma. The clinical presentation and the typical location of the findings centred in the pars interarticularis help to distinguish a stress injury from an acute traumatic fracture

(Tofte et al., 2017). The spondylolysis and surrounding bone marrow oedema can probably be assessed with MRI (Campbell et al., 2005). Still, the evidence of MRI's sensitivity is not fully concurrent (Yamaguchi, Skaggs, et al., 2012). However, it seems that MRI's performance can be improved with high-resolution T1W sequences optimised for bony structures (Ang et al., 2016) or with novel ultrashort time-to-echo (ZTE) techniques (Finkenstaedt et al., 2019; Kaniewska et al., 2023), achieving image quality clinically comparable to CT.

#### 2.6.5.4 Imaging appearances of normal skeletal maturation

Every radiologist working with paediatric imaging must be aware of the fundamentals of skeletal maturation (Augusto et al., 2022; Igbinoba & Jaramillo, 2023). One potential pitfall in the MRI of acute paediatric trauma is the physiological high T2 signal at the physis and metaphyseal spongiosa of the secondary ossification centres (Jaimes et al., 2014). This can be misinterpreted as traumatic oedema if the normal anatomy and development of the ossification centres are not kept in mind. On the other hand, an unfused vertebral ring apophysis (Woo et al., 2018; Costa et al., 2021), apophyseal injuries (Lawson et al., 1987), and other calcifications not related to acute injury are readily distinguished from fractures with absence of bone marrow oedema.

#### 2.6.5.5 Cerebrospinal fluid pulsation artifacts

The pulsatile movement of cerebrospinal fluid causes flow void artefacts, especially on T2W sequences. The artefacts can occur anywhere in the subarachnoid spaces. In the spine, they are most prominent in the cervical and thoracic regions (Enzmann et al., 1986; Lisanti et al., 2007). Usually, the hazy and poorly delineated appearance of flow void artefacts differentiates them from hematomas or dilated venous structures.

#### 2.6.5.6 Motion artefacts

MRI is very susceptible to patient movement. The data acquisition is done gradually, and the patient must stay still during each imaging sequence to successfully gather all the data required. In the paediatric population, motion artefacts may become an issue even more often than with adults. The appropriate child-friendly circumstances help obtain sufficient image quality (Lerwick, 2016; Runge et al., 2018; Dégeilh et al., 2023). Still, sedation or anaesthesia is sometimes mandatory. Fast and optimised imaging protocols (Singh et al., 2023; Spampinato et al., 2023) should be utilised, and the most crucial MRI sequences (e.g. STIR) should be obtained first.

### 2.6.5.7 Metal-induced artefacts

Compared to the adult population, ferromagnetic implants and other foreign bodies in the spinal region are uncommon among children. Dental braces are usual, but unlike brain MRI, they seldom cause significant problems in spinal imaging. Braces inflict susceptibility artefacts, but the extent of the artefact is usually limited outside the spine. Naturally, information about any ferromagnetic foreign body within the patient must be ensured for safety reasons, and the possible effects on MRI safety and image quality must be carefully assessed (ACR Committee on MR Safety, 2020; Peschke et al., 2021).

# 3 Aims

The general aim of this thesis was to retrospectively assess the feasibility of MRI as a primary diagnostic imaging modality in children and adolescents with suspected spinal trauma. The Emergency Radiology Department of Turku University Hospital pioneered MRI as an emergency imaging tool in 2013 and has used it for various indications ever since. MRI has been used extensively in the emergency imaging of paediatric brain and spine instead of CT to reduce exposure to ionising radiation. Based on clinical experience, the MRI has been safe, and the clinical outcomes of the patients who have undergone emergency spinal MRI have been acceptable. Still, the scientific evidence regarding the practice has been scarce. Specifically, the aims of the thesis were:

1. To evaluate the utility of emergency MRI as a primary and sole imaging modality in paediatric low-impact spinal trauma by assessing the clinical outcomes of these patients.

2. To further assess the utility and reliance of emergency spinal MRI by (1) studying the additional clinical value of the follow-up imaging in children and adolescents with whom the emergency MRI was part of the primary diagnostic workup of suspected spinal trauma and (2) studying the additional value of MRI performed after an emergency spinal CT.

3. To study the value of the need for brain imaging in paediatric patients with suspected spinal injury by assessing the traumatic brain MRI findings in patients who had undergone spine and brain MRI concurrently at the emergency department.

# 4 Materials and Methods

## 4.1 Study design and patients

All studies are retrospective single-centre chart review studies conducted at Turku University Hospital. The study samples consist of patients of under 18 years of age who have undergone an emergency MRI because of a suspected spinal injury in the Department of Emergency Radiology of Turku University Hospital between April 1, 2023, and August 31, 2021. All studies include different population samples. The sizes and demographic characteristics of the different study samples are demonstrated in Table 2.

**Table 2.** Demographic characteristics of patients in study samples.

| | STUDY I | STUDY II | STUDY III | STUDY IV |
|---|---|---|---|---|
| **NUMBER OF PATIENTS** | 396 | 127 | 179 | 100 |
| **AGE, MEAN (SD)** | 11.5 (3.6) | 11.3 (3.2) | 11.7 (4.4) | 12.8 (4.2) |
| **AGE, MEDIAN (RANGE)** | 12 (0–17) | 12 (2–17) | 13 (0–17) | 14 (1–17) |
| **FEMALE, *N* (%)** | 215 (54) | 55 (43) | 93 (52) | 44 (44) |
| **MALE, *N* (%)** | 181 (46) | 72 (57) | 86 (48) | 56 (56) |

### 4.1.1 Clinical outcome following magnetic resonance imaging as first-line imaging in low-impact pediatric spine trauma: a single-center retrospective observational study (I)

The study assessed the utility of MRI as first-line imaging in low-impact paediatric spinal trauma by reviewing the clinical outcomes of the patients who had an MRI as a first-line imaging method after a spinal trauma. Our hypothesis was, that MRI is accurate and safe to use as a first-line or only diagnostic tool in paediatric spinal trauma. The inclusion criteria for the study were (1) first-line emergency spinal MRI due to acute trauma, (2) age under 18, and (3) low-impact injury. A low-impact injury was defined as an injury not severe enough to trigger the standardised trauma team protocol. Exclusion criteria were (1) severely altered consciousness, (2) unstable hemodynamics, and (3) suspected child abuse. The final study sample consisted of 396 patients. The primary reference standard was the need for surgical intervention during the follow-up. The follow-up time was defined as the period from the emergency MRI to the last date the patient was known to reside in the municipality within our hospital district. As our hospital is the only centre within the district providing paediatric spinal surgery, it is justified to assume that any late-onset problems because of primarily missed injuries requiring surgical consultation would have emerged in the medical records.

### 4.1.2 Outcomes of follow-up imaging after pediatric spinal trauma confirmed with magnetic resonance imaging (II)

The study assessed the additional yield of follow-up imaging in paediatric patients with spinal trauma when an emergency MRI was part of an initial diagnostic workup. We hypothesised, that the follow-up imaging in patients with MRI-confirmed spinal injury does not yield additional value, if the injury does not have features suggesting instability. The inclusion criteria for the study were (1) emergency spinal MRI due to acute trauma, (2) age under 18, and (3) follow-up imaging after the initial hospitalisation period. The patients who underwent surgery after the first-line imaging studies (n=6) were excluded; the final sample consisted of 127 patients. The particular focus was on two groups: patients with FE follow-up imaging and patients with only thoracolumbar compression fractures of height loss of no more than 30% of the vertebral height. In analysing the utility of FE imaging in cervical spine injuries, the MRI findings strongly indicating instability were the following: PLC injury, anterior tension band disruption, burst fracture, and disruption of the ligaments of the CCJ.

### 4.1.3 Utility of brain imaging in pediatric patients with a suspected accidental spinal injury but no brain injury-related symptoms (III)

The study assessed the additional yield of brain imaging in paediatric patients with emergency spinal MRI because of suspected spinal trauma and concurrent brain MRI. Our hypothesis was, that concurrent brain MRI with a spinal MRI in patients without brain injury symptoms is not useful even in the presence of spinal injury. The inclusion criteria for the study were (1) emergency spinal MRI and (2) concurrent brain MRI. The patients with (1) primary MRI indications other than trauma and (2) patients with trauma but no Pediatric Emergency Care Applied

Research Network (PECARN) risk factors for cervical spine injury or reasoned clinical suspicion for thoracolumbar spine injury (based on symptoms and clinical findings) were excluded. The study sample included 179 patients. At our institution, the diagnostic workup of children with a suspicion of non-accidental trauma is carried out in the Department of Pediatric Radiology, and these patients are, therefore, not included in this study. The clinical decision-making rules for paediatric head trauma were not systematically used in the emergency department and could, therefore, not be applied to the analysis. However, the level of consciousness, neurological symptoms and deficits, headache, nausea, and other possible brain injury-related symptoms were descriptively recorded in the medical records. The utility of brain MRI was also assessed in patients having a high energy trauma (motor vehicle accident, pedestrian struck by car, bicycle crash, fall from a height of at least two meters).

### 4.1.4 Imaging outcomes of MRI after CT in pediatric spinal trauma – a single center experience (IV)

The study assessed the additional diagnostic value of spinal MRI after CT in paediatric patients by comparing the imaging findings and clinical outcomes in patients who had undergone both imaging modalities. Our hypothesis was that MRI's ability to detect unstable spinal injuries in the paediatric population is at least comparable to the CT. The inclusion criteria for the study were (1) spinal MRI due to acute trauma, (2) spinal emergency CT ≤5 days before spinal MRI and (3) age under 18. The final study sample included 100 patients.

### 4.1.5 Previously unpublished observations of injured spinal levels in paediatric patients with a suspected cervical spine trauma

We analysed the craniocaudal distribution of traumatic MRI findings within a subsample of paediatric patients having (1) primary suspicion of cervical spine injury, (2) at least one PECARN risk factor for cervical spine injury, and (3) acute traumatic findings on emergency spinal MRI. The sample included 116 patients. In this analysis, all traumatic MRI findings were registered according to the vertebral level of the finding (or findings) and every injured vertebral level was registered as a separate injury, but the type of injury was not assessed, only the surgically treated injuries were noted separately. That is, per-lesion-like analysis was performed, but the severity of the injury was not considered apart from surgically treated injuries. The purpose of this analysis was to see how the MRI findings with paediatric trauma patients with suspected cervical spine injuries were distributed. Because CCJ injuries are known to be more prevalent in young children, patients were put in two age groups: 2–7 years old (*n*=18) and 8–17 years old (*n*=98) to study the incidence of CCJ injuries in different age groups of this sample.

Our hypothesis and practical rationale were that the children with suspected cervical spine trauma have more traumatic findings in the upper thoracic spine than what is previously noticed.

## 4.2 Imaging practices, image analysis and imaging protocols

The study was entirely retrospective. Hence, all imaging examinations included in the analysis were referred by the responsible physician, usually a paediatric orthopaedic surgeon. The decision on whether the MRI was performed with or without anaesthesia or sedation was based on the verdict of the responsible physician. Still, the standard clinical practice was to scan the children fully awake whenever possible. The radiographers asked for reassessment if sufficient image quality could not be achieved without sedation. The analysis is based on the original radiology reports extracted from RIS. Original images were occasionally reviewed using PACS in a targeted manner if an essential detail of the initial radiology report was unclear because of a reporting mishap, for example, a typing error. We did not perform systematic retrospective image review, because the main goal of the study was to assess the use of emergency MRI in clinical patient care using clinical outcomes as a reference standard.

### 4.2.1 Emergency MRI protocols

The emergency MRI examinations included in the study were performed using a Philips Ingenia 3-tesla system with a Philips dStream coil system (Philips Healthcare, Best, Netherlands). The standard spine MRI protocol included sagittal T1-weighted, sagittal and axial T2-weighted and sagittal and coronal short tau inversion recovery (STIR) sequences (Table 3). The dedicated small field of view (FOV) proton density- and T2-weighted series were used for the craniocervical junction (occipital bone–second cervical vertebra, C0–C2) when needed (Table 4). The brain MRI protocol (study III) included at least the following sequences: axial T2-weighted, isotropic 3D T1-weighted, isotropic 3D FLAIR, axial diffusion-weighted (DWI), and axial susceptibility-weighted (DWI) sequences. A contrast medium was not used in trauma MRI.

In sagittal and coronal sequences, large FOV was routinely used. Cervical spine MRI was extended to cover upper third of the thoracic spine and lumbar spine MRI was extended to cover lower third of the thoracic spine.

**Table 3.** Sequence parameters in routine emergency magnetic resonance imaging.

| | CERVICAL SPINE | | | | | THORACOLUMBAR SPINE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **PARAMETER** | SAG T1 | SAG T2 | SAG STIR | COR STIR | AX T2 | SAG T1 | SAG T2 | SAG STIR | COR STIR | AX T2 |
| **TR (MS)** | 550 | 3584 | 3305 | 3721 | 5717 | 683 | 4955 | 4391 | 5778 | 3601 |
| **TE (MS)** | 7 | 100 | 60 | 60 | 95 | 8 | 100 | 60 | 60 | 100 |
| **FLIP ANGLE** | 80 | 90 | 90 | 90 | 90 | 80 | 90 | 90 | 90 | 90 |
| **SLICE THICKNESS (MM)** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 3 |
| **SLICE SPACING** | 3.3 | 3.3 | 3.6 | 3.6 | 3.3 | 3.3 | 3.3 | 3.3 | 4.4 | 3.3 |
| **NUMBER OF SLICES** | 15 | 15 | 15 | 18 | 35 | 21 | 21 | 19 | 20 | 51 |
| **MATRIX SIZE** | 480 x 480 | 448 x 448 | 480 x 480 | 432 x 432 | 320 x 320 | 384 x 384 | 432 x 432 | 512 x 512 | 432 x 432 | 320 x 320 |

**Table 4.** Sequence parameters in emergency magnetic resonance imaging of craniocervical junction.

| | CRANIOCERVICAL JUNCTION | | |
|---|---|---|---|
| **PARAMETER** | SAGITTAL PD | CORONAL PD | AXIAL T2 |
| **TR (MS)** | 2500 | 2500 | 5902 |
| **TE (MS)** | 20 | 20 | 80 |
| **FLIP ANGLE** | 90 | 90 | 90 |
| **SLICE THICKNESS (MM)** | 2.5 | 2.5 | 2.5 |
| **SLICE SPACING** | 2.75 | 2.75 | 2.75 |
| **NUMBER OF SLICES** | 22 | 16 | 27 |
| **MATRIX SIZE** | 400 x 400 | 320 x 320 | 320 x 320 |

### 4.2.2 Emergency CT protocols

The emergency CT examinations were performed with a GE Revolution scanner (GE Healthcare, Chicago, Illinois, USA) or Toshiba Aquilition One (Toshiba Medical Systems, Otawara, Japan). In cervical spine CT, a contrast medium was not used. In most cases, the thoracolumbar spine CT was imaged as a part of a whole-body trauma CT; therefore, an iodine-based contrast medium was administered after the cervical spine CT.

### 4.2.3 Follow-up imaging protocols

The follow-up MRIs, CTs, and conventional radiographs were obtained using devices by various vendors. The EOS system (ATEC Spine, Inc., Carlsbad, CA) was often used in follow-up with conventional radiograph imaging, both static and dynamic studies.

## 4.3 Clinical outcome and other clinical variables

All clinical variables were retrospectively extracted from the medical records. The injury mechanism, symptoms, and clinical findings are noted as how the responsible physician originally recorded them. PECARN risk factors for paediatric cervical spine injury were not recorded initially, but the data needed to calculate the PECARN risk factors retrospectively was always available. The treatment strategies of the individual patients were based on the verdict of the responsible paediatric surgeon. The Turku University Hospital is the only centre in the district providing paediatric spinal surgery. Therefore, we have assumed that the potential complications or primarily missed injuries would have emerged in the medical records.

## 4.4 Statistical analysis

The author performed the statistical analysis using IBM SPSS Statistic's Package for Mac (versions 28 and 29, IBM Corporation, Armonk, NY). The results are expressed as the number of cases ($n$), percentage, range, median, mean, and standard deviation (SD). The normality of probability distributions was tested using the Kolmogorov–Smirnov and Shapiro–Wilk tests. The Mann–Whitney U test was used to compare means for non-normally distributed variables. Proportions of categorical variables were compared with the Pearson Chi-square ($X^2$) test and Fisher's exact test. One-way ANOVA was used to compare the means of multiple groups. $P$-values $< 0.05$ were considered statistically significant.

## 4.5 Ethical aspects

The study was conducted with the permission of the hospital district board (T66/2019). Due to the study's retrospective nature, no informed consent or ethics committee approval was needed.

# 5 Results

## 5.1 Clinical outcome following magnetic resonance imaging as first-line imaging in low-impact pediatric spine trauma: a single-center retrospective observational study (I)

The injury mechanisms, follow-up information and outcomes among the patients in study sample I are presented in the Table 5. Of 396 patients, 114 (28.8%) had any traumatic MRI findings, while 282 (71.2%) did not. Only 3/396 patients (0.8%) of the whole sample required surgical treatment, all operatively treated injuries were trampoline accidents. The clinical follow-up period was six months or more with 376 patients. Within this group, no primarily missed injuries requiring specific treatment occurred during the follow-up.

**Table 5.** Injury mechanism, follow-up information and outcomes in study I.

| | TOTAL (*N=396)* | MRI POSITIVE (*N*=114) | MRI NEGATIVE (*N*=282) | *P*-VALUE* |
|---|---|---|---|---|
| ***INJURY MECHANISM, N (%)*** | | | | |
| **FALL** | 109 (27.5) | 26 (22.8) | 83 (29.4) | 0.267 |
| **TRAMPOLINE** | 69 (17.4) | 36 (31.6) | 33 (11.7) | <0.001 |
| **CONTACT SPORTS** | 50 (12.6) | 8 (7.0) | 42 (14.9) | 0.031 |
| **GYMNASTICS** | 32 (8.1) | 13 (11.4) | 19 (6.7) | 0.155 |
| **HORSEBACK RIDING** | 29 (7.3) | 7 (6.1) | 22 (7.8) | 0.673 |
| **MOPED, ALL-TERRAIN VEHICLE** | 26 (6.6) | 2 (1.8) | 24 (8.5) | 0.013 |
| **WINTER SPORTS** | 18 (4.5) | 7 (6.1) | 11 (3.9) | 0.425 |
| **VIOLENCE BY ANOTHER CHILD** | 18 (4.5) | 4 (3.5) | 14 (5.0) | 0.605 |
| **CAR ACCIDENT** | 14 (3.5) | 4 (3.5) | 10 (3.5) | 1.000 |
| **PEDESTRIAN STRUCK BY CAR** | 3 (0.8) | 1 (0.9) | 2 (0.7) | 1.000 |
| **OTHER (BICYCLE, KICK SCOOTER, DIVING, ACCIDENTAL HIT IN THE HEAD)** | 28 (7.1) | 6 (5.3) | 22 (7.8) | 0.398 |

| | TOTAL (*N=396)* | MRI POSITIVE (*N*=114) | MRI NEGATIVE (*N*=282) | *P*-VALUE* |
|---|---|---|---|---|
| ***FOLLOW-UP INFORMATION*** | | | | |
| **FOLLOW-UP APPOINTMENT WITH PAEDIATRIC ORTHOPAEDIC SURGEON** | 108 (27.3) | 79 (69.3) | 29 (10.3) | |
| **LAST APPOINTMENT WITH A PAEDIATRIC ORTHOPAEDIC SURGEON, WEEKS AFTER EMERGENCY MRI, MEDIAN (RANGE)** | 6 (1–110) | 6 (1–110) | 2 (1–104) | |
| **TOTAL FOLLOW-UP PERIOD, MONTHS AFTER EMERGENCY MRI, MEDIAN (RANGE)** | 41 (0–98) | 41 (0–98) | 41 (0–98) | |
| ***OUTCOMES IN PATIENTS WITH A FOLLOW-UP TIME OF SIX MONTHS OR MORE, N (%)*** | | | | |
| **NO PERMANENT CONSEQUENCES** | 358 (95.2) | 106 (93.0) | 260 (96.7) | 0.112 |
| **PROLONGED PAIN** | 16 (4.3) | 7 (6.5) | 9 (3.3) | 0.256 |
| **POSTOPERATIVE JUNCTIONAL KYPHOSIS** | 1 (0.3) | 1 (0.9) | - | 0.287 |

* Proportions of the patients in the groups “MRI POSITIVE” and “MRI NEGATIVE” were compared using the Mann-Whitney *U*-test.

### 5.1.1 MRI findings in the study sample

The most common injury type in the group of patients with traumatic MRI findings was bony injury (78/114, 68.4%). The ligamentous injury was seen in 41/114 patients (36.0%), and the most commonly affected ligamentous structure was the interspinous ligament, which was injured in 26/114 (22.8%) patients with traumatic findings, either as an isolated injury or in combination with other ligaments. Epidural hematoma was seen in one patient (0.9%), AARF/AARS in 2 patients (1.8%), facet or UV-joint injury in 8 patients (7.0%), intervertebral disc injury in 3 patients (2.6%), and muscle injury in 26 patients (22.8%). Isolated soft tissue oedema was seen in 10 patients (8.8%). A combination of different injury types was found in 38/114 patients (33.3%).

Regarding the injury levels, the proportions of isolated one-level injuries were as follows: craniocervical junction 11/114 (9.6%), subaxial cervical spine 25/114 (21.9%), thoracic spine 33/114 (28.9%), lumbar spine 12/114 (10.5%), and sacral spine 8/114 (7.0%). However, an injury affecting multiple spinal levels was seen in 25/114 patients (21.9%). Of all patients with traumatic findings, non-contiguous injury with spared levels between the injured levels was seen in 27/114 patients. (23.7%). Patient age was not statistically significantly associated with the level of injury (one-way ANOVA, *P*=0.190). Ligamentous injuries were more common in the cervical spine ($X^2=33.2$, $P<0.001$), and bony injuries were more common in the subcervical spine ($X^2=59.4$, $P<0.001$).

### 5.1.2 The need for sedation or anaesthesia

Of the study sample, 377 patients (95.2%) were scanned without anaesthesia or sedation, while 16 (4%) were scanned following sedation and spontaneous breathing, and only three patients (0.8%) required general anaesthesia with intubation. The need for sedation or anaesthesia was mainly limited to children younger than five (mean 3.5 years). MRI artefacts were noted in five reports (1.3%), of which three were minor without warranting additional imaging. Only one scan had to be suspended before obtaining diagnostic images because of insufficient cooperation, but the scan was completed the next day. The patients were scanned in 376/396 (95%) cases on admission or the next day.

No anaesthesia- or MRI-related adverse events occurred primarily nor during the follow-up period.

### 5.1.3 Reporting radiologists and complementary imaging

Most of the MRI reports included in the study (378/396, 95.4%) were written by a fellowship-trained neuroradiologist, musculoskeletal radiologist or emergency radiologist with more than seven years of experience in radiology. The rest were written by other board-certified radiologists with more than five years of experience in radiology (16/396, 4.0%) and radiology residents with more than three years of experience in radiology (2/396, 0.5%).

Complementary emergency CT imaging was used in 15 cases. All of these were suggested by the radiologist on call to further examine suspected bony injuries. In one case, extensive motion artefacts on MRI impacted the decision to perform CT after MRI. None of the complementary CTs revealed injuries not seen in the MRI.

## 5.2 Outcomes of follow-up imaging after pediatric spinal trauma confirmed with magnetic resonance imaging (II)

The injury mechanisms, emergency MRI findings and the overview of the follow-up imaging in the study sample (*n*=127) are presented in Table 6.

**Table 6.** Injury mechanism, emergency MRI findings and overview of follow-up imaging in study II.

| ***MECHANISM OF INJURY*** | ***N* (%)** |
|---|---|
| **TRAMPOLINE** | 31 (24) |
| **SPORTS** | 28 (22) |
| **FALL** | 27 (21) |
| **TRAFFIC** | 25 (20) |
| **HORSEBACK RIDING** | 8 (6) |
| **VIOLENCE BY ANOTHER CHILD** | 4 (3) |
| **DIVING** | 2 (2) |
| **OTHER/UNKNOWN** | 2 (2) |
| ***FOLLOW-UP IMAGING OVERVIEW*** | **MEAN (SD) RANGE** |
| **FIRST FOLLOW-UP IMAGING (DAYS)** | 24 (21) 1–171 |
| **LAST FOLLOW-UP IMAGING (DAYS)** | 58 (177) 1–2011 |
| **NUMBER OF FOLLOW-UP IMAGING** | 1.6 (0.1) 1–5 |
| ***GENERAL CHARACTERISATION OF EMERGENCY MRI FINDINGS*** | ***N* (%)** |
| **BONY INJURY ONLY** | 60 (47) |
| **BONY AND LIGAMENTOUS INJURY** | 30 (24) |
| **LIGAMENTOUS INJURY ONLY** | 25 (20) |
| **OTHER (INTERVERTEBRAL DISC, MUSCLE, RETROCLIVAL HEMATOMA WITHOUT VISIBLE STRUCTURAL INJURY)** | 3 (2) |
| **NO TRAUMATIC FINDINGS ON MRI** | 9 (7) |
| ***INJURED SPINAL LEVELS ON EMERGENCY MRI*** | ***N* (%)** |
| **CERVICAL SPINE** | 40 (32) |
| **THORACIC SPINE** | 32 (25) |
| **LUMBOSACRAL SPINE** | 13 (10) |
| **MULTIPLE LEVELS** | 33 (26) |
| **NONE** | 9 (7) |

### 5.2.1 Patients with uncomplicated thoracolumbar compressions

There were 42 patients with one or more thoracolumbar contusions or compression fractures with a height loss of 30% or less but without complicating factors such as burst-type fracture or ligamentous injury. In this group, the short-term follow-up imaging did not lead to additional treatment in any patient. Height loss increased in

1/42 patients (2%) from 5% to 10%, while all other uncomplicated contusions or compressions remained unchanged (Figures 3 & 4).

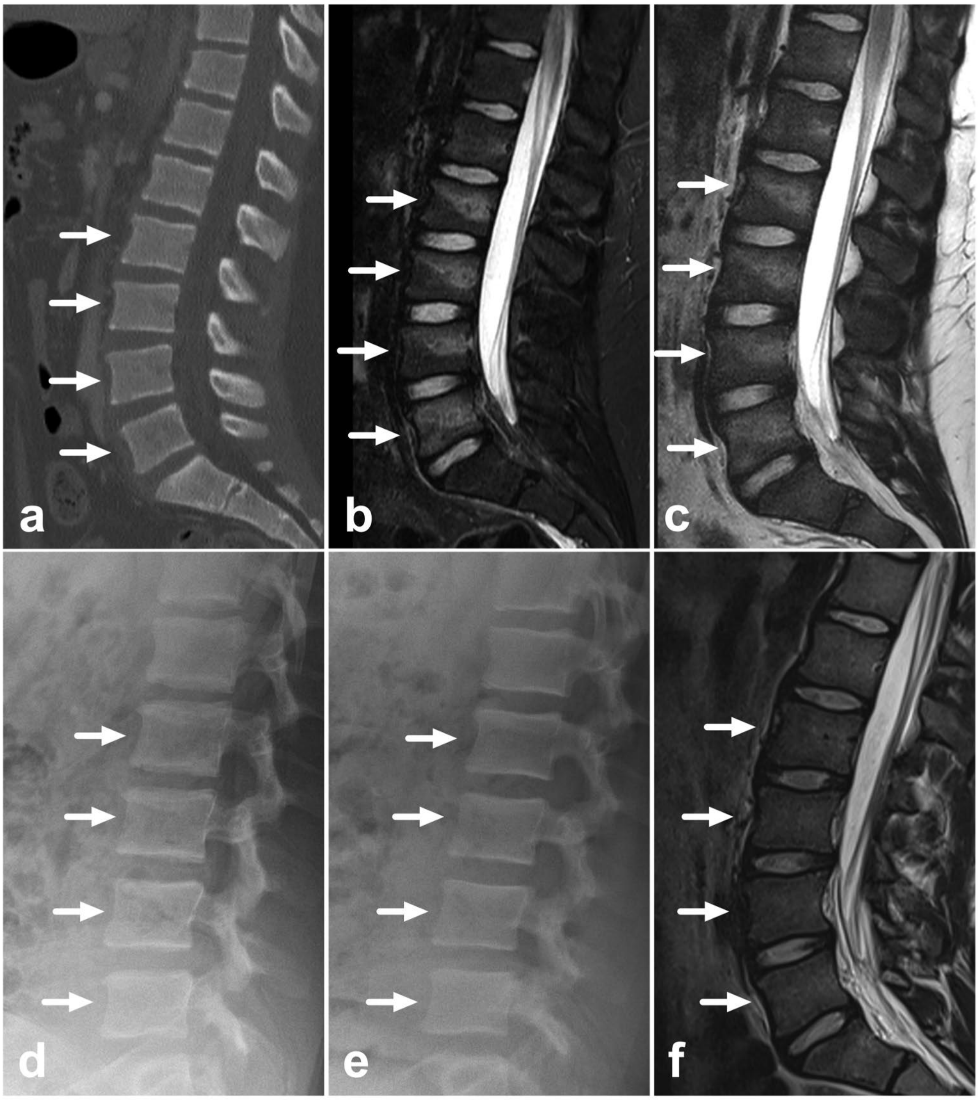

**Figure 4.** Minor compression fractures (arrows) of L2-L5 in a 14-year-old boy with polytrauma after a fall. The emergency MRI was obtained due to neurological symptoms in the lower limbs. The findings did not progress in the follow-up imaging. A follow-up MRI with unremarkable findings was performed one year after the injury because of prolonged back pain. **a** Trauma CT **b** Sagittal short tau inversion recovery, the emergency MRI **c** Sagittal T2-weighted, the emergency MRI **d** Lateral plain radiograph two weeks after the injury (sitting position due to calcaneal fractures). **e** Lateral plain radiograph six weeks after the injury (sitting position due to calcaneal fractures). **f** Sagittal T2-weighted, follow-up MRI 1 year after the injury. Images retrieved without identifiers from the PACS of Turku University Hospital.

### 5.2.2 Patients with flexion-extension follow-up imaging

FE follow-up imaging was used with 54 patients suffering from a cervical spine injury. Of these, 36 were scanned with conventional FE radiographs, six with FE MRI and ten with both. If the emergency MRI did not suggest unstable features, follow-up FE imaging was unremarkable. Still, in contrast, 6/14 (43%) of the patients with presumably unstable findings on emergency had signs of instability in FE follow-up imaging ($p$<0.001). Five patients were referred to surgical treatment because of persistent instability after the conservative treatment attempt. The value of FE MRI was also assessed in the follow-up imaging. None of the 16 FE MRI follow-up examinations revealed findings not visible in the emergency or static follow-up MRI or gave additional information compared to conventional FE radiographs. A sufficient range of motion was harder to achieve in FE MRI than in conventional FE radiographs.

In addition to the patients described under the FE imaging, one patient was referred to surgical treatment due to follow-up imaging findings. This patient's emergency MRI findings were compression fractures on C4 and C5, bilateral C4/5 facet joint capsule injuries, partial interspinous tear, ligamentum flavum detachment from the vertebral arches on levels C4-C5, and slight kyphotic malalignment on the level C4-C5, but no unequivocal ligamentous discontinuity. After one week, the kyphosis demonstrated significant progression in conventional follow-up radiographs despite the collar immobilisation. A posterolateral instrumented fusion was performed.

## 5.3 Utility of brain imaging in pediatric patients with a suspected accidental spinal injury but no brain injury-related symptoms (III)

We found 455 patients fulfilling the inclusion criteria. After excluding 266 patients who were scanned because of other indications than trauma and 15 patients without PECARN risk factors for cervical spine injury or reasoned suspicion of thoracolumbar trauma, the final study sample consisted of 179 patients. The injury mechanisms, the prevalence of possible brain injury-related symptoms, and the emergency MRI in the study sample are presented in Table 7.

The seniority of the radiologist reporting the MRI studies was as follows: Fellowship-trained subspecialists in neuro- or emergency radiology (with at least seven years of experience in radiology) reported 144/179 (80.4%) of the MRIs, other consultant radiologists (with at least five years of experience in radiology) reported 34/179 (19.0%) and one MRI (0.6%) was reported by a radiologist in training (with at least three years of experience).

**Table 7.** Injury mechanism, prevalence of brain injury-related symptoms, and emergency MRI findings in study III.

| ***MECHANISM OF INJURY*** | ***N* (%)** |
|---|---|
| **FALL** | 71 (40) |
| **MOTOR VEHICLE ACCIDENT** | 33 (18) |
| **SPORTS** | 33 (18) |
| **BICYCLE OR KICK SCOOTER** | 12 (7) |
| **HORSEBACK RIDING** | 11 (6) |
| **VIOLENCE BY ANOTHER CHILD** | 8 (5) |
| **TRAMPOLINE** | 6 (3) |
| **OTHER (DIVING, HANGING, UNKNOWN)** | 5 (3) |
| ***PRESENCE OF BRAIN INJURY-RELATED SYMPTOMS*** | ***N* (%)** |
| **POTENTIAL BRAIN INJURY SYMPTOMS** | 137 (76) |
| **NO POTENTIAL BRAIN INJURY SYMPTOMS** | 42 (24) |
| ***INCIDENCE OF TRAUMATIC FINDINGS ON BRAIN MRI*** | ***N* (%)** |
| **DIFFUSE AXONAL INJURY** | 11 (6) |
| **HEMORRHAGIC CONTUSION** | 11 (6) |
| **SKULL OR SKULL BASE FRACTURE** | 8 (5) |
| **EPIDURAL HEMATOMA** | 6 (3) |
| **SUBDURAL HEMATOMA** | 4 (2) |
| **SUBARACHNOIDAL HEMORRHAGE** | 1 (1) |
| **INTRAVENTRICULAR HEMORRHAGE** | 1 (1) |
| ***INCIDENCE OF TRAUMATIC FINDINGS ON SPINE MRI*** | ***N* (%)** |
| **LIGAMENTOUS INJURY** | 20 (11) |
| **OSSEOUS INJURY** | 19 (11) |
| **SOFT TISSUE INJURY ONLY** | 11 (6) |
| **SPINAL CORD INJURY** | 1 (1) |

### 5.3.1 Traumatic brain MRI findings

Of all patients without traumatic findings on brain MRI ($n$=154), 112 had potential brain injury symptoms, and 42 were asymptomatic. There were 25 patients with traumatic findings on brain MRI, and all of them had symptoms suggesting brain injury ($X^2$=8.908, *P*=0.003). In the subgroup of patients with high-energy trauma, 14 symptomatic patients had traumatic brain MRI findings, and no asymptomatic patients had findings on the brain MRI (*P*=0.028, Fisher's exact test).

Of the patients having traumatic brain MRI findings, seven had traumatic spinal MRI findings, while 18 did not have spinal injury, while the number of patients without traumatic brain injury findings were 29 (spinal injury on MRI) and 125 (no spinal injury on MRI). The brain injury findings and spine injury findings were not associated ($X^2$=1.125, *P*=0.289).

### 5.3.2 Non-traumatic brain MRI findings

Non-traumatic brain MRI findings were found in 18 patients with potential brain injury-related symptoms and five asymptomatic patients, while the proportions of the symptomatic and asymptomatic patients among the group without non-traumatic brain MRI findings were 119 and 37, respectively ($X^2$=0.044, *P*=0.83). Of the patients with non-traumatic brain MRI findings, two patients were treated due to the brain MRI findings. One patient had an infection that was clinically suspected in addition to the acute trauma, and the mastoidal infection was treated. The second patient receiving treatment because of non-traumatic brain finding had an actual incidental finding, Chiari malformation with syrinx, and was electively operated on later.

## 5.4 Imaging outcomes of MRI after CT in pediatric spinal trauma – a single center experience (IV)

We found 100 patients meeting the inclusion criteria. The demographic characteristics are found in Table 2, and injury mechanisms, proportions of suspicious spinal level, descriptive values of delay from CT to MRI and the treatment used in the study population are described in Table 8. Of the patients treated with surgery, one had two separate injuries that were operated.

**Table 8.** Injury mechanism, proportions of most suspected spinal levels, delays from CT to MRI, and the treatment used in the population of study IV.

| ***MECHANISM OF INJURY*** | ***N* (%)** |
|---|---|
| **TRAFFIC** | 45 (45) |
| **FALL** | 23 (23) |
| **CONTACT SPORTS AND GYMNASTICS** | 14 (14) |
| **HORSEBACK RIDING** | 7 (7) |
| **TRAMPOLINE** | 6 (6) |
| **DIVING** | 3 (3) |
| **TRAMPOLINE** | 6 (3) |
| **HANGING** | 2 (2) |
| ***PRIMARILY SUSPICIOUS SPINE REGION*** | ***n* (%)** |
| **CERVICAL SPINE** | 82 (82) |
| **THORACOLUMBAR SPINE** | 18 (18) |
| ***DELAY FROM CT TO MRI*** | **DAYS** |
| **MEAN (SD)** | 0.8 (1.1) |
| **RANGE (MEDIAN)** | 0–5 (1) |
| ***INJURIES TREATED WITH IMMOBILISATION*** | ***n* (%)** |
| **SURGICAL FIXATION INCLUDING HALO BRACE** | 7 (7) |
| **RIGID CERVICAL COLLAR OR THORACIC EXTENSION BRACE** | 36 (36) |
| **GLISSON’S TRACTION** | 6 (6) |
| **NO IMMOBILISATION** | 51 (51) |

### 5.4.1 The accuracy of CT and MRI reports in describing unstable injuries

All injuries requiring surgical treatment were accurately described in MRI reports. CT reports were accurate in six surgically treated injuries, but in 1/7 (14%) CT reports of surgically treated patients, the unstable features of the injury were missed. With this patient, an MRI was performed after CT to evaluate the wedge-shaped thoracic vertebrae with suspected compression fractures further. However, besides the compression fractures, MRI revealed an unstable PLC disruption. In retrospect, the widened interspinous distance suggesting ligamentous injury could have already been noted on CT.

### 5.4.2 Accuracy of CT regarding any traumatic finding using MRI as a reference standard

When the accuracy of CT reports was assessed using MRI as a reference standard in detecting any traumatic findings, the number of true positive reports was 35/100 (35%), true negative reports 27/100 (27%), false positive reports 25/100 (25%) and false negative reports 13/100 (13%). Overall diagnostic accuracy of CT using MRI as a reference standard was 0.61 (95% confidence interval 0.52–0.72, sensitivity was 0.73 (0.58–0.85), and specificity was 0.51 (0.37–0.66). The most common missed injuries on CT reports were PLC injury and CCJ injury (5/13, 38% each), followed by soft tissue injury (2/13, 15%) and osseous injury (1/13, 8%). The most common erroneously suspected traumatic finding on CT reports (false positive) was CCJ injury (15/25, 60%), followed by bony injury (7/25, 28%) and PLC injury (3/25, 12%). Even if no osseous injuries requiring surgery were missed, many fractures or bone contusions seen on MRI were not detected on CT reports. At most, MRI revealed previously unnoticed injuries in seven vertebrae in one patient, while two patients had osseous injuries not seen in CT in six separate vertebrae.

### 5.4.3 Accuracy of CT reports among readers with different training levels using MRI as a reference standard

The proportions of reporting radiologists with different training levels regarding emergency CT reports were as follows: in training, at least three years of experience in radiology (25/100, 25%), board-certified radiologists, at least five years of experience in radiology (20/100, 20 %), fellowship-trained neuro- musculoskeletal- or emergency radiologist with at least seven years of experience in radiology (55/100, 55%). The proportions of radiologists with different training levels reporting MRI studies were 1/100 (1%), 16/100 (16%), and 83/100 (83%), respectively. The accuracy of the CT reports regarding the traumatic findings among radiologists with different training levels was assessed using an MRI report as a reference standard. Among the radiologists in training, the balanced accuracy of CT reports was 0.43 (95% confidence interval 0.20–0.68), among board-certified radiologists CT reports' balanced accuracy was 0.59 (0.25–0.88) and among fellowship-trained subspecialists, respectively. The difference in the accuracy of CT reports between the training levels was not statistically significant ($X^2$=2.544, p=0.280) in this sample.

# 5.5 Previously unpublished observations of injured spinal levels in paediatric patients with a suspected cervical spine trauma

## 5.5.1 Characteristics of the patient sample

This sample included 116 patients with age range of 2–17, mean age of 11.2 years (SD=3.7), and median age of 12 years. Of this sample, 66/116 (57%) were males and 50/116 (43%) were females. Injury mechanisms were as follows: Trampoline 35/116 (30%), sports 28/116 (24%), traffic 23/116 (20%), fall 21/116 (18%), violence 6/116 (5%), and horseback riding 3/116 (3%).

## 5.5.2 Longitudinal distribution of traumatic findings on MRI

The incidence of traumatic MRI findings in (1) CCJ, (2) subaxial spine an (3) both combined in children younger than eight years and eight years, or more are presented in Table 9.

**Table 9.** Craniocervical junction injuries, subaxial injuries and combined injuries in two age groups.

| | CRANIOCERVICAL JUNCTION | SUBAXIAL CERVICAL SPINE OR THORACIC SPINE | CCJ AND SUBAXIAL SPINE COMBINED | *P*-VALUE |
|---|---|---|---|---|
| **2–7 YEARS (*N*=18)** | 2 | 14 | 2 | 0.428 |
| **8–17 YEARS (*N*=98)** | 24 | 59 | 15 | |

There was no statistically significant difference in the distribution of injured levels between the two age groups when all patients with injury findings on MRI were considered (*P*=0.428, Fisher's exact test).

Regarding surgically treated injuries, the two surgically treated CCJ injuries were from the younger age group (two years and 7 years old patients). Of patients with subaxial cervical spine or thoracic spine injury, seven were operated on. Of these, one patient was from the younger age group (two years old), while the others were from the older age group, the ages 11, 11, 12, 12, 13, and 17. One surgically treated patient had injury solely on the subcervical spine, at level Th1-Th2. The other surgically treated patients had findings also in lower in cervical spine, even if the injury extended to the thoracic spine.

When all separate spinal levels with traumatic MRI findings were assessed, no thoracic spine injuries were seen in patients younger than five years. Among patients older than five, thoracic spine injuries were relatively common (Figure 5).

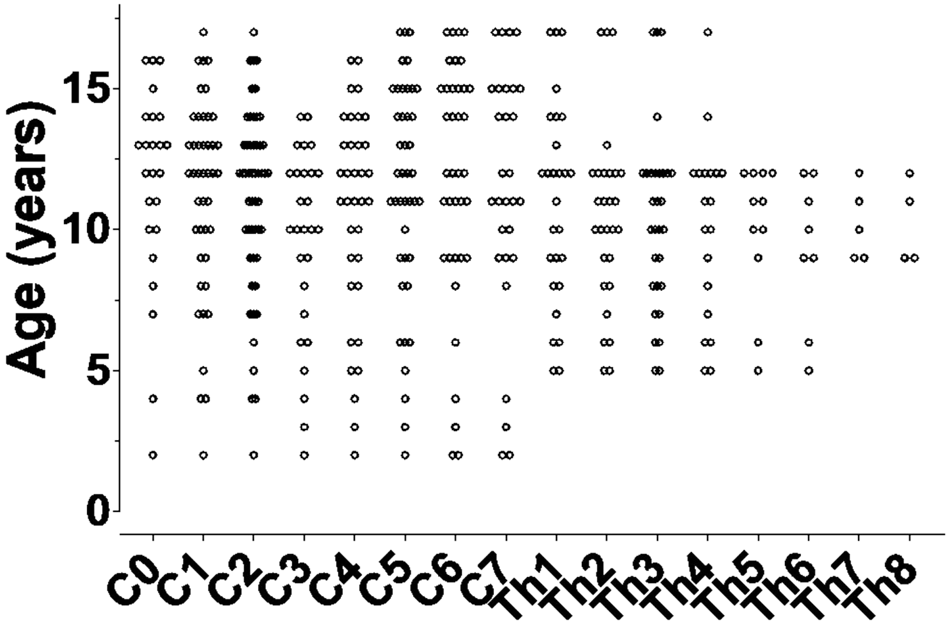

**Figure 5.** All spinal levels with an injury finding on emergency MRI in different age groups. A circle represents one injured vertebral level, i.e., one patient with multiple injured vertebral levels represents several circles.

# 6 Discussion

## 6.1 Key findings

Our retrospective analysis of spinal MRI findings performed for paediatric trauma patients in the Emergency Radiology Department of Turku University Hospital between April 1, 2013, and August 31, 2021, strengthens the confidence in using MRI as an emergency imaging modality in paediatric spinal trauma. With 396 patients having a low-impact trauma, MRI was used as first-line imaging without reported MRI- or anaesthesia-related adverse effects. Of these, 376 had a clinical follow-up period of six months or more, and no missed injuries occurred during the follow-up. In the sample of 127 patients with follow-up imaging after spinal emergency MRI, the added value of the follow-up imaging was low if the injury did not demonstrate unstable features in the primary MRI. With 100 patients having undergone emergency CT and MRI, no injuries requiring surgical treatment were missed on MRI. In this sample, one unstable cervical spine injury was not reported with CT, but the unstable features are visible on CT in retrospect. Therefore, MRI and CT can both be interpreted to be highly accurate in detecting unstable paediatric spinal injuries in the emergency setting. With 179 patients having undergone concurrent MRIs of the brain and spine because of trauma, we found no intracranial injuries, with 42 patients who had no clinical findings or symptoms that could suggest brain injury. Hence, we suggest that brain imaging might not be useful for paediatric trauma patients who are asymptomatic regarding head injury, even if the patient is nevertheless undergoing spinal MRI. Despite the paediatric study population, the need for sedation with spontaneous breathing or intubation and anaesthesia was low. In the sample of Study I, 16/396 patients (4%) required sedation or anaesthesia and in the sample of Study III, consisting of patients with more severe injury mechanisms, 18/179 (10%) required sedation or anaesthesia. The need for sedation or anaesthesia was mostly limited to children younger than five.

Overall, spinal emergency MRI was safe and highly accurate in detecting spinal injuries requiring surgical treatment. However, regarding the injury outcomes, MRI was not superior to CT, and the clinical significance of injuries seen only in MRI remains unclear. Further studies are needed to tell if MRI is cost-effective and beneficial to an individual patient or if it should be recommended as a primary imaging modality in paediatric spinal trauma.

## 6.2 Utility of emergent magnetic resonance imaging in paediatric spinal trauma

### 6.2.1 Diagnostic accuracy

The main goal of medical imaging in suspected paediatric spinal trauma is to detect unstable injuries potentially requiring surgical treatment. When imaging is needed, CR or CT is usually used initially (The Royal College of Radiologists 2014; Kadom et al., 2019; McAllister et al., 2019). If clinical suspicion is raised or the findings on CR or CT are unequivocal regarding potential unstable ligamentous injury, MRI is recommended (Kadom et al., 2019). From the perspective of patient outcomes, the additional diagnostic yield of MRI after CR or CT without signs of trauma has been studied with varying results. Moore et al. found MRI to be significantly more sensitive and specific than CR (Moore et al., 2017), and considering obtunded or otherwise non-examinable patients, a meta-analysis by Schoenfeld et al. (Schoenfeld et al., 2010) and a newer study by Al-Sarheed et al. (Al-Sarheed et al., 2020) suggested cervical spine MRI should be performed even after unremarkable CT. On the other hand, several studies have found CT alone to be sufficient to exclude unstable cervical spine injury (Qualls et al., 2015; Derderian et al., 2019), even with the CCJ injuries, if the presence of retroclival hematoma is carefully screened (Stephenson et al., 2023). In thoracolumbar fractures, MRI after CT did not change the treatment plan (Franklin et al., 2019).

MRI as a sole imaging modality in paediatric spinal trauma has not been examined before. Still, the accuracy of MRI in detecting unstable injuries is proven to be excellent (R. P. Lee et al., 2022). Henry et al. compared the sensitivity of MRI and CT in detecting paediatric spinal injuries, finding MRI to yield high sensitivity in excluding osseous injuries compared to CT, while CT had low sensitivity in excluding soft tissue/ligamentous injuries compared to CT.

Our results of the Study I suggest MRI provides 100 % sensitivity in detecting injuries requiring surgical treatment among paediatric patients with low-impact injuries. The result concords with the findings by Lee et al. (R. P. Lee et al., 2022), who concluded that MRI alone is sufficient to exclude unstable spinal injury even if the patients in their study sample had undergone CT before MRI because their sample also included patients with high-impact trauma.

The results of Study II demonstrated that follow-up imaging did not reveal any findings requiring immobilisation if the emergency MRI did not demonstrate unstable features, further strengthening the confidence in emergency spinal MRI. The subject has not been studied from this perspective before.

Regarding diagnostic accuracy in revealing unstable injuries, the findings of Study IV are well in line with the previous literature. MRI promptly demonstrated all injuries needing surgical fixation. Still, just as in many previous studies, MRI did not reveal unstable injuries not visible in CT (Qualls et al., 2015; Derderian et al., 2019; Franklin et al., 2019; Stephenson et al., 2023). More injuries were seen with MRI than with CT. Like in the work of Henry et al., MRI revealed more injuries than CT, both ligamentous/soft tissue and osseous injuries (M. Henry, Riesenburger, et al., 2013).

### 6.2.2 Feasibility and safety of spinal MRI in the emergency department

A major concern with the use of MRI in the paediatric population is the need for sedation or anaesthesia. (Callahan & Cravero, 2022) In our study samples, most examinations were obtained on the patients fully awake, 380/396 (95%) in Study I and 161/179 (90%) in Study III, including patients with high-impact trauma. Only three patients in Study I (0.8%) and one patient (0.6%) in Study III were intubated to have MRIs performed. Light sedation with spontaneous breathing was used for 16 (4%) and 11 (6%) patients, respectively. The need for anaesthesia was mostly limited to patients aged five years or younger, concordant with the recent literature about the subject suggesting that the need for sedation or anaesthesia is mainly needed in pre-school-aged children (Runge et al., 2018; Dégeilh et al., 2023; Thestrup et al., 2023). No anaesthesia-related adverse events were reported with patients in studies I or III. In studies II and IV, the need for sedation or anaesthesia was not registered.

In Study I, we assessed the feasibility of spinal MRI with paediatric patients in the emergency department. Only 1/396 scans (0.3%) had to be suspended due to insufficient cooperation, and this scan was successfully performed the next day without sedation or anaesthesia. In 1/396 cases (0.3%), a complementary CT was performed on the radiologist's initiative because of extensive motion artefacts; all the other scans were completed with sufficient image quality. With our Emergency Radiology Department MRI scanner dedicated to urgent imaging, we were able to perform 377/396 (95%) scans right on admission or the next day. The delays were shorter among the patients with traumatic MRI findings, suggesting that the clinical assessment of the need for imaging was adequate. Obviously, most radiology units do not have a dedicated emergency scanner, but our results show that practice like this is viable.

No MRI-related safety events were reported in our study sample. Based on the incidence estimated in previous literature, 1–3 adverse events could have occurred in our sample (Jaimes et al., 2018; Snyder et al., 2018; R. P. Lee et al., 2022). However, in our emergency department, paediatric spinal MRI appears very safe.

### 6.2.3 Clinical value and cost-effectiveness

MRI's most recognised advantages over CR and CT are the absence of ionising radiation and superior soft tissue contrast, allowing direct assessment of the ligamentous structures, intraspinal haematomas and the spinal cord. (Kadom et al., 2019; McAllister et al., 2019). Obviously, these advantages were present in our studies, too. In Study IV, we demonstrated that MRI revealed many more stable, sometimes subtle injuries than CT. The clinical significance of the injuries not seen in CT (or CR) is unclear. Treatment of different spinal injuries is beyond the scope of this thesis. Still, as radiologists, we need to be aware of the meaning and value of the examinations and reports we provide.

According to the previous literature and our current results, unstable injuries are almost invariably seen in CT and MRI. These injuries require immobilisation with internal surgical fixation, halo immobilisation or collar/brace to prevent further neurological damage and enable healing. Injuries with unequivocal stability and fractures without unstable features are still treated with a rigid cervical collar or thoracic extension brace in many cases, however, the most suitable treatment with these patients is unknown (Rozzelle et al., 2013; Murphy et al., 2015; Singer et al., 2016; Copley et al., 2019; Konovalov et al., 2020; Dauleac et al., 2021). A recent study by Belov et al. found that paediatric patients with multiple non-complicated compression fractures, also seen in CR and CT, recover well without immobilisation (Belov et al., 2024).

With extensive use of MRI, many previously unseen injuries are revealed. Currently, no specific treatment can be provided to patients with non-structural, stable injuries like bone bruises, minor ligamentous strains, or muscle injuries. We also saw a substantial amount of thoracic spine injuries without unstable features among patients with suspected cervical spine trauma (Figure 3). Many patients are found to have injuries with even more benign appearance than, e.g. the ones described by Belov et al. (Below et al., 2024). We can speculate that thorough imaging and interpretation of the MRI findings may help reduce the anxiety of the patient and the parents, help them accept temporary symptoms, and, therefore, reduce the number of future healthcare system contacts. But does one need an MRI to tell that trauma leads to tissue damage? Apparently, no. One of the key issues seems to be the low specificity of the clinical decision-making rules (Slaar et al., 2017; Luehmann et al., 2020; Phillips et al., 2021; Sires et al., 2022), leading to an excessive number of findings with limited clinical value, or without any findings, especially with CR. On the other hand, given the potential fatality of missed unstable spinal injury, the sensitivity of the decision-making rules must be very high. In this era of defensive medicine and imaging overuse (Chen et al., 2015; Tong et al., 2016; Ten Brinke et al., 2021), balance is difficult to achieve.

Based on the results of Studies I and IV and the unpublished observations (5.5), the children have lots of injuries that are invisible on CR and CT and do not require any specific treatment but might be painful. The unpublished observations demonstrate that many non-structural injuries, like bone bruises, are also seen in the thoracic spine of school-aged children with suspected *cervical* spine trauma (Figures 3 & 5). Based on these results alone, it is impossible to reliably assess whether the thoracic spine MRI has additional value with individual patients having this kind of injury. Probably not if the cervical spine MRI is routinely extended to the level of Th2, as none of the surgically treated patients had injuries only below the level of Th2 if the primary suspicion was of cervical spine injury. However, our findings may help the physicians in informing patients after unremarkable CR or CT at the emergency. The patient and the parents can be informed that an unremarkable CT is highly accurate in excluding serious injuries, but there can still be tissue damage in soft tissue and even in osseous structures. Therefore, symptoms may last for weeks.

The cost-effectiveness of MRI in the emergent diagnostic workup of paediatric spinal trauma is unclear. Frank et al. calculated twenty years ago (Frank et al., 2002), that emergency MRI decreases the overall expenditure with the obtunded, hospitalised paediatric trauma patients with suspected cervical spine trauma, but for our understanding, the subject hasn't been studied since. Some of our studies' results may be beneficial regarding cost-effectiveness. Study II found that the number of follow-up and FE imaging can be reduced with emergency MRI as unstable features of the injury are readily distinguished or excluded. Study III found that head imaging is not useful in paediatric trauma patients, even in the presence of imaging-confirmed spinal injury, if the patient does not have symptoms suggesting brain injury. The result supports relying on the clinical decision-making rules (Babl et al., 2017) also in the presence of spinal injury. In a recent large French study (Roche et al., 2023) the upper cervical spine fracture had statistically significant association with the traumatic findings on head CT. However, in their study the spine fracture was not assessed as an independent risk factor for TBI, therefore not being in contradiction with our results. Still, if upper cervical spine fracture is accompanied with other risk factors, the probability of TBI seems to be high. Study IV demonstrated the proportion of false positive traumatic findings in paediatric spinal CT being substantial, especially among less experienced readers, leading to subsequent MRI scans. In these circumstances, MRI as first-line imaging can be seen as an effective alternative, as unnecessary CT can be avoided. However, the problem of false positive CTs can also be reduced with more experienced readers (Hassan et al., 2020). If an MRI is performed, eventual anaesthesia is a significant expense. Studies

I and III demonstrated that most patients over five years old can be scanned awake. Overall, the cost-effectiveness of different imaging modalities in the diagnostic workup of suspected paediatric spinal trauma is unclear and should be properly studied in the future.

## 6.3 Limitations of the study and generalizability of the results

This study's most obvious and important limitations arise from the inherited weaknesses of a retrospective study design. The decisions about the patients' diagnostic workflow, treatment, or follow-up were not standardised, and the rationales behind the choices cannot be consistently assessed in retrospect. Still, the relatively small size of our centre seems to have the protocols reasonably consistent. A consultant paediatric orthopaedic surgeon (or, to a lesser extent, neurosurgeon or orthopaedic surgeon) was invariably involved in the decision-making, and within this group of professionals, the policies and the methods seem to have had pretty strong mutual agreement. The data in the medical records and the radiology reports was primarily not recorded systematically. Therefore, there was a variation in the extent and thoroughness of the information between individual patients.

The actual diagnostic accuracy of MRI could not be examined because the retrospective image review was not performed. However, the primary goal of this study was to examine the utility of paediatric spinal trauma MRI in a real-life setting. Ultimately, the final patient outcome might be an even more important imaging endpoint than the absolute diagnostic accuracy de facto. The radiologists reporting the imaging studies, especially emergency MRIs, were mostly very experienced professionals. The proportion of fellowship-trained subspecialists in neuroradiology, musculoskeletal radiology or emergency radiology was 80,4% in Study III, 83,0% in Study IV, and 95,4% in Study I. More study is needed to confirm if the utility of and accuracy regarding patient outcomes of emergency MRI in paediatric spinal trauma is acceptable if no such experienced radiologists are available. Naturally, it is always recommended to have experienced radiologists working also outside office hours (Hassan et al., 2020).

The patient demographics in the study yield limitations to the generalisation of the results. Relatively few preschool-aged children were included. Maybe because of this, severe CCJ injuries were very rare among the study sample. We did not have patients with a suspected non-accidental trauma included in the study. Still, the usefulness of MRI in non-accidental spinal injuries has been studied before (Kadom et al., 2014; Baerg et al., 2017; M. K. Henry et al., 2021; Karmazyn et al., 2022). These studies also include mostly infants and toddlers, demonstrating the accuracy of MRI with young children. Similarly, only a few patients with spinal cord injury were included in our study sample, but the high accuracy of MRI in cord imaging has already been proven before ((Modic, Weinstein, Pavlicek, Starnes, Boumphrey & Duchesneau 1983; Kadom et al., 2019; McAllister et al., 2019).

Overall, despite the limitations described, we see that the study's background, implementation, and results reflect the reality of an emergency department in a tertiary care trauma centre in Northern Europe without significant biases.

## 6.4 Future perspectives

Our studies show that emergency MRI *can* be used in paediatric spinal trauma. The most important subject for future studies would be the cost-benefit analysis, i.e., if MRI *should* be utilised as an emergency imaging modality. In addition to the monetary aspects, the real long-term adverse effects of ionising radiation exposure of CR and CT need to be better understood. These are complex questions that will probably not be answered anytime soon. In the meantime, the technical applications to fasten the acquisitions, e.g. AI-based image reconstruction techniques, should be used to improve MRI’s availability and to minimise the need for anaesthesia or sedation to scan the patients.

From a broader perspective, the need for more specific clinical decision-making rules in the diagnostic workup of suspected paediatric spinal trauma is evident. As presented in Study III, the decision-making rules in the suspected paediatric brain (PECARN, CATCH, CHALICE) injury provide reasonable specificity without sacrificing the high sensitivity. The corresponding criteria for assessing the need for imaging in paediatric spinal trauma (PECARN, NEXUS, CCR) are highly sensitive but poorly specific (Slaar et al., 2017; Luehmann et al., 2020; Phillips et al., 2021; Sires et al., 2022), leading to an excessive number of imaging. The increasing trend of emergency imaging overuse (Chen et al., 2015; Tong et al., 2016; Marin et al., 2020; Ten Brinke et al., 2021) is harmful to society, the healthcare system and the patient, no matter how accurate the imaging is.

# 7 Conclusions

MRI seems to be feasible and safe as an emergency imaging modality in suspected paediatric spinal trauma. In a low-impact trauma, it can be used as a first-line and sole imaging modality, at least when the readers are experienced. MRI is highly accurate; however, it is not superior to CT in demonstrating paediatric spinal injuries requiring surgical treatment. If an emergency MRI does not raise a suspicion of a potentially unstable injury, the short-term follow-up imaging does not alter the treatment plan, i.e., it is not of benefit. The children without any symptoms suggesting brain injury do not seem to need brain imaging, regardless of the suspected or confirmed spinal injury. Most children aged five years or older can be scanned with an MRI fully awake. Still, further studies are needed to verify if the MRI should be considered the primary modality in paediatric spinal trauma or if its role should be as it has been for decades – a complementary problem-solving tool after CR or CT.

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*Aapo Sirén*

# References

ACR Committee on MR Safety. (2020). ACR Manual on MR Safety. Version 1.0. *American College of Radiology*. https://www.acr.org/-/media/ACR/Files/Radiology-Safety/MR-Safety/Manual-on-MR-Safety.pdf

Adelgais, K. M., Grossman, D. C., Langer, S. G., & Mann, F. A. (2004). Use of helical computed tomography for imaging the pediatric cervical spine. *Academic Emergency Medicine*, *11*(3), 228–236. https://doi.org/10.1111/j.1553-2712.2004.tb02202.x

Ahuja, C. S., Wilson, J. R., Nori, S., Kotter, M. R. N., Druschel, C., Curt, A., & Fehlings, M. G. (2017). Traumatic spinal cord injury. *Nature Reviews Disease Primers*, *3*(1), 17018. https://doi.org/10.1038/nrdp.2017.18

Al Mukhtar, A., Bergenfeldt, H., Edelhamre, M., Vedin, T., Larsson, P.-A., & Öberg, S. (2022). The epidemiology of and management of pediatric patients with head trauma: A hospital-based study from Southern Sweden. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine*, *30*(1), 67. https://doi.org/10.1186/s13049-022-01055-9

Al-Sarheed, S., Alwatban, J., Alkhaibary, A., Babgi, Y., Al-Mohamadi, W., Masuadi, E. M., Al Babtain, I., & Azzubi, M. (2020). Cervical spine clearance in unconscious pediatric trauma patients: A level 1 trauma center experience. *Child's Nervous System*, *36*(4), 811–817. https://doi.org/10.1007/s00381-019-04440-5

Amis, E. S., Butler, P. F., Applegate, K. E., Birnbaum, S. B., Brateman, L. F., Hevezi, J. M., Mettler, F. A., Morin, R. L., Pentecost, M. J., Smith, G. G., Strauss, K. J., & Zeman, R. K. (2007). American College of Radiology White Paper on Radiation Dose in Medicine. *Journal of the American College of Radiology*, *4*(5), 272–284. https://doi.org/10.1016/j.jacr.2007.03.002

Andropoulos, D. B. (2018). Effect of Anesthesia on the Developing Brain: Infant and Fetus. *Fetal Diagnosis and Therapy*, *43*(1), 1–11. https://doi.org/10.1159/000475928

Ang, E. C., Robertson, A. F., Malara, F. A., O'Shea, T., Roebert, J. K., Schneider, M. E., & Rotstein, A. H. (2016). Diagnostic accuracy of 3-T magnetic resonance imaging with 3D T1 VIBE versus computer tomography in pars stress fracture of the lumbar spine. *Skeletal Radiology*, *45*(11), 1533–1540. https://doi.org/10.1007/s00256-016-2475-7

Arbuthnot, M., & Mooney, D. P. (2017). The sensitivity and negative predictive value of a pediatric cervical spine clearance algorithm that minimizes computerized tomography. *Journal of Pediatric Surgery*, *52*(1), 130–135. https://doi.org/10.1016/j.jpedsurg.2016.10.031

Arkader, A., Warner, W. C., Tolo, V. T., Sponseller, P. D., & Skaggs, D. L. (2011). Pediatric Chance Fractures: A Multicenter Perspective. *Journal of Pediatric Orthopaedics*, *31*(7), 741–744. https://doi.org/10.1097/BPO.0b013e31822f1b0b

Atlas S., Regenbogen V., Rogers L. E., & Kim K. S. (1986). The Radiographic Characterization of Burst Fractures of the Spine. *American Journal of Roentgenology*, 147, 575–562.

Audic, B., & Maury, M. (1969). Secondary vertebral deformities in childhood and adolescence: Abstract. *Spinal Cord*, *7*(1), 10–16. https://doi.org/10.1038/sc.1969.4

Augusto, A. C. D. L., Goes, P. C. K., Flores, D. V., Costa, M. A. F., Takahashi, M. S., Rodrigues, A. C. O., Padula, L. C., Gasparetto, T. D., Nogueira-Barbosa, M. H., & Aihara, A. Y. (2022). Imaging

Review of Normal and Abnormal Skeletal Maturation. *RadioGraphics*, *42*(3), 861–879. https://doi.org/10.1148/rg.210088

Avellino, A. M., Mann, F. A., Grady, M. S., Chapman, J. R., Ellenbogen, R. G., Alden, T. D., & Mirza, S. K. (2005). The misdiagnosis of acute cervical spine injuries and fractures in infants and children: The 12-year experience of a level I pediatric and adult trauma center. *Child's Nervous System*, *21*(2), 122–127. https://doi.org/10.1007/s00381-004-1058-4

Aydıngöz, Ü., Yıldız, A. E., & Ergen, F. B. (2022). Zero Echo Time Musculoskeletal MRI: Technique, Optimization, Applications, and Pitfalls. *RadioGraphics*, *42*(5), 1398–1414. https://doi.org/10.1148/rg.220029

Babl, F. E., Borland, M. L., Phillips, N., Kochar, A., Dalton, S., McCaskill, M., Cheek, J. A., Gilhotra, Y., Furyk, J., Neutze, J., Lyttle, M. D., Bressan, S., Donath, S., Molesworth, C., Jachno, K., Ward, B., Williams, A., Baylis, A., Crowe, L., … Dalziel, S. R. (2017). Accuracy of PECARN, CATCH, and CHALICE head injury decision rules in children: A prospective cohort study. *The Lancet*, *389*(10087), 2393–2402. https://doi.org/10.1016/S0140-6736(17)30555-X

Baerg, J., Thirumoorthi, A., Vannix, R., Taha, A., Young, A., & Zouros, A. (2017). Cervical spine imaging for young children with inflicted trauma: Expanding the injury pattern. *Journal of Pediatric Surgery*, *52*(5), 816–821. https://doi.org/10.1016/j.jpedsurg.2017.01.049

Banerjee, P., & Thomas, M. (2019). CT scans to exclude spine fractures in children after negative radiographs may lead to increase in future cancer risk. *European Journal of Orthopaedic Surgery & Traumatology*, *29*(5), 983–988. https://doi.org/10.1007/s00590-019-02396-5

Beckmann, N. M., Chinapuvvula, N. R., Zhang, X., & West, O. C. (2020). Epidemiology and Imaging Classification of Pediatric Cervical Spine Injuries: 12-Year Experience at a Level 1 Trauma Center. *American Journal of Roentgenology*, *214*(6), 1359–1368. https://doi.org/10.2214/AJR.19.22095

Belov, S., Grahn, P., Kivisaari, R., Helenius, I., & Ahonen, M. (2024). Activity-restriction only as treatment yields positive outcomes in pediatric spinal compression fractures: A prospective study of 47 patients at medium-term follow-up. *Acta Orthopaedica*, *95*, 8–13. https://doi.org/10.2340/17453674.2024.35161

Benedetti, P. F., Fahr, L. M., Kuhns, L. R., & Hayman, L. A. (2000). MR Imaging Findings in Spinal Ligamentous Injury. *American Journal of Roentgenology*, *175*(3), 661–665. https://doi.org/10.2214/ajr.175.3.1750661

Boice, J. D. (2015). Radiation epidemiology and recent paediatric computed tomography studies. *Annals of the ICRP*, *44*(1_suppl), 236–248. https://doi.org/10.1177/0146645315575877

Bosch De Basea Gomez, M., Thierry-Chef, I., Harbron, R., Hauptmann, M., Byrnes, G., Bernier, M.-O., Le Cornet, L., Dabin, J., Ferro, G., Istad, T. S., Jahnen, A., Lee, C., Maccia, C., Malchair, F., Olerud, H., Simon, S. L., Figuerola, J., Peiro, A., Engels, H., … Cardis, E. (2023). Risk of hematological malignancies from CT radiation exposure in children, adolescents and young adults. *Nature Medicine*, 29, 3111–3119. https://doi.org/10.1038/s41591-023-02620-0

Brenner, D. J., Elliston, C. D., Hall, E. J., & Berdon, W. E. (2001). Estimated Risks of Radiation-Induced Fatal Cancer from Pediatric CT. *American Journal of Roentgenology*, *176*(2), 289–296. https://doi.org/10.2214/ajr.176.2.1760289

Callahan, M. J., & Cravero, J. P. (2022). Should I irradiate with computed tomography or sedate for magnetic resonance imaging? *Pediatric Radiology*, *52*(2), 340–344. https://doi.org/10.1007/s00247-021-04984-2

Campbell, R. S. D., Grainger, A. J., Hide, I. G., Papastefanou, S., & Greenough, C. G. (2005). Juvenile spondylolysis: A comparative analysis of CT, SPECT and MRI. *Skeletal Radiology*, *34*(2), 63–73. https://doi.org/10.1007/s00256-004-0878-3

Canadian STOPP Consortium National Pediatric Bone Health Working Group, Jaremko, J. L., Siminoski, K., Firth, G. B., Matzinger, M. A., Shenouda, N., Konji, V. N., Roth, J., Sbrocchi, A. M., Reed, M. H., O'Brien, M. K., Nadel, H., McKillop, S., Kloiber, R., Dubois, J., Coblentz, C., Charron, M., & Ward, L. M. (2015). Common normal variants of pediatric vertebral development that mimic fractures: A pictorial review from a national longitudinal bone health study. *Pediatric Radiology*, *45*(4), 593–605. https://doi.org/10.1007/s00247-014-3210-y

Cattell, H. S., & Filtzer, D. L. (1965). Pseudosubluxation and other normal variations in the cervical spine in children. A study of one hundred and sixty children. *The Journal of Bone and Joint Surgery. American Volume*, *47*(7), 1295–1309.

Cattrysse, E., Barbero, M., Kool, P., Gagey, O., Clarys, J. P., & Van Roy, P. (2007). 3D morphometry of the transverse and alar ligaments in the occipito–atlanto–axial complex: An in vitro analysis. *Clinical Anatomy*, *20*(8), 892–898. https://doi.org/10.1002/ca.20559

Cauldwell, C. (2011). Anesthesia risks associated with pediatric imaging. *Pediatric Radiology*, *41*(8), 949–950. https://doi.org/10.1007/s00247-011-2160-x

Chandra, J., Sheerin, F., Lopez De Heredia, L., Meagher, T., King, D., Belci, M., & Hughes, R. J. (2012). MRI in acute and subacute post-traumatic spinal cord injury: Pictorial review. *Spinal Cord*, *50*(1), 2–7. https://doi.org/10.1038/sc.2011.107

Chen, J., Majercik, S., Bledsoe, J., Connor, K., Morris, B., Gardner, S., Scully, C., Wilson, E., Dickerson, J., White, T., & Dillon, D. (2015). The prevalence and impact of defensive medicine in the radiographic workup of the trauma patient: A pilot study. *The American Journal of Surgery*, *210*(3), 462–467. https://doi.org/10.1016/j.amjsurg.2015.03.016

Chokshi, F. H., Munera, F., Rivas, L. A., Henry, R. P., & Quencer, R. M. (2011). 64-MDCT angiography of blunt vascular injuries of the neck. *American Journal of Roentgenology*, 196(3), W309–W315. doi: 10.2214/AJR.10.4548.

Chupik, C., Hernandez, J. A., & Swischuk, L. E. (2004). Cervical spine trauma in children under 5 years: Productivity of CT. *Emergency Radiology*, *10*(4), 176–178. https://doi.org/10.1007/s10140-003-0320-5

Compagnon, R., Ferrero, E., Leroux, J., Lefevre, Y., Journeau, P., Vialle, R., Glorion, C., Violas, P., Chalopin, A., Odent, T., Haddad, E., Nallet, J., Garin, C., Choufani, E., Langlais, T., & Sales de Gauzy, J. (2020). Epidemiology of spinal fractures in children: Cross-sectional study. *Orthopaedics & Traumatology: Surgery & Research*, *106*(7), 1245–1249. https://doi.org/10.1016/j.otsr.2020.06.015

Copley, P. C., Tilliridou, V., Kirby, A., Jones, J., & Kandasamy, J. (2019). Management of cervical spine trauma in children. *European Journal of Trauma and Emergency Surgery*, *45*(5), 777–789. https://doi.org/10.1007/s00068-018-0992-x

Costa, L., De Reuver, S., Kan, L., Seevinck, P., Kruyt, M. C., Schlosser, T. P. C., & Castelein, R. M. (2021). Ossification and Fusion of the Vertebral Ring Apophysis as an Important Part of Spinal Maturation. *Journal of Clinical Medicine*, *10*(15), 3217. https://doi.org/10.3390/jcm10153217

Cowen, A. R., Kengyelics, S. M., & Davies, A. G. (2008). Solid-state, flat-panel, digital radiography detectors and their physical imaging characteristics. *Clinical Radiology*, *63*(5), 487–498. https://doi.org/10.1016/j.crad.2007.10.014

Cui, L. W., Probst, M. A., Hoffman, J. R., & Mower, W. R. (2016). Sensitivity of plain radiography for pediatric cervical spine injury. *Emergency Radiology*, *23*(5), 443–448. https://doi.org/10.1007/s10140-016-1417-y

Dauleac, C., Mottolese, C., Beuriat, P.-A., Szathmari, A., & Di Rocco, F. (2021). Superiority of thoracolumbar injury classification and severity score (TLICS) over AOSpine thoracolumbar spine injury classification for the surgical management decision of traumatic spine injury in the pediatric population. *European Spine Journal*, *30*(10), 3036–3042. https://doi.org/10.1007/s00586-020-06681-4

Dawkins, R. L., Miller, J. H., Ramadan, O. I., Lysek, M. C., Kuhn, E. N., Rocque, B. G., Conklin, M. J., Tubbs, R. S., Walters, B. C., Agee, B. S., & Rozzelle, C. J. (2018). Thoracolumbar Injury Classification and Severity Score in children: A reliability study. *Journal of Neurosurgery: Pediatrics*, *21*(3), 284–291. https://doi.org/10.3171/2017.7.PEDS1720

de Gauzy, J. S., Jouve, J.-L., Violas, P., Guillaume, J.-M., Coutié, A.-S., Chaumoitre, K., Launay, F., Bollini, G., Cahuzac, J.-P., & Accadbled, F. (2007). Classification of Chance Fracture in Children

Using Magnetic Resonance Imaging. *SPINE*, *32*(2), E89–E92. https://doi.org/10.1097/01.brs.0000252092.27345.1a

Dégeilh, F., Lacombe-Barrios, J., Tuerk, C., Lebel, C., Daneault, V., El-Jalbout, R., Gravel, J., Deschênes, S., Dubois, J., Lapierre, C., Gagnon, I., Dehaes, M., Luu, T. M., & Beauchamp, M. H. (2023). Behavioral-play familiarization for non-sedated magnetic resonance imaging in young children with mild traumatic brain injury. *Pediatric Radiology*, *53*(6), 1153–1162. https://doi.org/10.1007/s00247-023-05592-y

Dellestable, F., & Gaucher, A. (1998). Clay-shoveler’s fracture. Stress fracture of the lower cervical and upper thoracic spinous processes. *Revue Du Rhumatisme (English Ed.)*, *65*(10), 575–582.

Denis F., Armstrong G. W., Searls K., & Matta L. (1984). Acute thoracolumbar burst fractures in the absence of neurologic deficit. A comparison between operative and nonoperative treatment. *Clinical Orthopaedics Related Research*, 189, 142–149.

Derderian, S. C., Greenan, K., Mirsky, D. M., Stence, N. V., Graber, S., Hankinson, T. C., Hubbell, N., Alexander, A., O’Neill, B. R., Wilkinson, C. C., & Handler, M. H. (2019). The utility of magnetic resonance imaging in pediatric trauma patients suspected of having cervical spine injuries. *Journal of Trauma and Acute Care Surgery*, *87*(6), 1328–1335. https://doi.org/10.1097/TA.0000000000002487

Dewan, M. C., Mummareddy, N., Wellons, J. C., & Bonfield, C. M. (2016). Epidemiology of Global Pediatric Traumatic Brain Injury: Qualitative Review. *World Neurosurgery*, *91*, 497-509.e1. https://doi.org/10.1016/j.wneu.2016.03.045

Dickman, C. A., Mamourian, A., Sonntag, V. K. H., & Drayer, B. P. (1991). Magnetic resonance imaging of the transverse atlantal ligament for the evaluation of atlantoaxial instability. *Journal of Neurosurgery*, *75*(2), 221–227. https://doi.org/10.3171/jns.1991.75.2.0221

Dreizin, D., Kim, W., Kim, J. S., Boscak, A. R., Bodanapally, U. K., Munera, F., & Stein, D. M. (2015). Will the Real SCIWORA Please Stand Up? Exploring Clinicoradiologic Mismatch in Closed Spinal Cord Injuries. *American Journal of Roentgenology*, *205*(4), 853–860. https://doi.org/10.2214/AJR.14.13374

Enzmann, D. R., Rubin, J. B., DeLaPaz, R., & Wright, A. (1986). Cerebrospinal fluid pulsation: Benefits and pitfalls in MR imaging. *Radiology*, *161*(3), 773–778. https://doi.org/10.1148/radiology.161.3.3786731

Farrell, C. A., Hannon, M., & Lee, L. K. (2017). Pediatric spinal cord injury without radiographic abnormality in the era of advanced imaging: *Current Opinion in Pediatrics*, *29*(3), 286–290. https://doi.org/10.1097/MOP.0000000000000481

Feng, Y.-P., Yang, T.-S., Chung, C.-H., Chien, W.-C., & Wong, C.-S. (2020). Early childhood general anesthesia exposure associated with later developmental delay: A national population-based cohort study. *PLOS ONE*, *15*(9), e0238289. https://doi.org/10.1371/journal.pone.0238289

Fiester, P., Rao, D., Soule, E., & Rahmathulla, G. (2021). Occipital condylar avulsion fractures in the acute trauma setting: Stable or unstable injury? *European Spine Journal*, *30*(10), 3128–3134. https://doi.org/10.1007/s00586-021-06949-3

Finkenstaedt, T., Siriwanarangsun, P., Achar, S., Carl, M., Finkenstaedt, S., Abeydeera, N., Chung, C. B., & Bae, W. C. (2019). Ultrashort Time-to-Echo Magnetic Resonance Imaging at 3 T for the Detection of Spondylolysis in Cadaveric Spines: Comparison With CT. *Investigative Radiology*, *54*(1), 32–38. https://doi.org/10.1097/RLI.0000000000000506

Flores, D. V., Mejía Gómez, C., Estrada-Castrillón, M., Smitaman, E., & Pathria, M. N. (2018). MR Imaging of Muscle Trauma: Anatomy, Biomechanics, Pathophysiology, and Imaging Appearance. *RadioGraphics*, *38*(1), 124–148. https://doi.org/10.1148/rg.2018170072

Forster, E. (1985). *Equipment for Diagnostic Radiography*. Springer Netherlands. https://doi.org/10.1007/978-94-009-4930-0

Frank, J. B., Lim, C. K., Flynn, J. M., & Dormans, J. P. (2002). The Efficacy of Magnetic Resonance Imaging in Pediatric Cervical Spine Clearance. *SPINE*, *27*(11), 1176–1179. https://doi.org/10.1097/00007632-200206010-00008

Franklin, D. B., Hardaway, A. T., Sheffer, B. W., Spence, D. D., Kelly, D. M., Muhlbauer, M. S., Warner, W. C., & Sawyer, J. R. (2019). The Role of Computed Tomography and Magnetic Resonance Imaging in the Diagnosis of Pediatric Thoracolumbar Compression Fractures. *Journal of Pediatric Orthopaedics*, *39*(7), e520–e523. https://doi.org/10.1097/BPO.0000000000001316

Frush, D. P., & Goske, M. J. (2015). Image Gently: Toward optimizing the practice of pediatric CT through resources and dialogue. *Pediatric Radiology*, *45*(4), 471–475. https://doi.org/10.1007/s00247-015-3283-2

Gaca, A. M., Barnhart, H. X., & Bisset, G. S. (2010). Evaluation of Wedging of Lower Thoracic and Upper Lumbar Vertebral Bodies in the Pediatric Population. *American Journal of Roentgenology*, *194*(2), 516–520. https://doi.org/10.2214/AJR.09.3065

Gargas, J., Yaszay, B., Kruk, P., Bastrom, T., Shellington, D., & Khanna, S. (2013). 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. *Journal of Trauma and Acute Care Surgery*, *74*(4), 1102–1107. https://doi.org/10.1097/TA.0b013e3182827139

Ghanem, N., Uhl, M., Müller, C., Elgeti, F., Pache, G., Kotter, E., Markmiller, M., & Langer, M. (2006). MRI and discography in traumatic intervertebral disc lesions. *European Radiology*, *16*(11), 2533–2541. https://doi.org/10.1007/s00330-006-0310-6

Gilcrease-Garcia, B. M., Deshmukh, S. D., & Parsons, M. S. (2020). Anatomy, Imaging, and Pathologic Conditions of the Brachial Plexus. *RadioGraphics*, *40*(6), 1686–1714. https://doi.org/10.1148/rg.2020200012

Goldman, M. (1996). Cancer Risk of Low-Level Exposure. *Science*, *271*(5257), 1821–1822. https://doi.org/10.1126/science.271.5257.1821

Gottumukkala, R. V., Kalra, M. K., Tabari, A., Otrakji, A., & Gee, M. S. (2019). Advanced CT Techniques for Decreasing Radiation Dose, Reducing Sedation Requirements, and Optimizing Image Quality in Children. *RadioGraphics*, *39*(3), 709–726. https://doi.org/10.1148/rg.2019180082

Medicines and Healhcare Products Regulatory Agency. (2021). Safety Guidelines for Magnetic Resonance Imaging Equipment in Clinical Use. Version 4.3. *Medicines and Healthcare products Regulatory Agency.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/958486/MRI_guidance_2021-4-03c.pdf

Groves, C. J., Cassar-Pullicino, V. N., Tins, B. J., Tyrrell, P. N. M., & McCall, I. W. (2005). Chance-Type Flexion-Distraction Injuries in the Thoracolumbar Spine: MR Imaging Characteristics. *Radiology*, *236*(2), 601–608. https://doi.org/10.1148/radiol.2362040281

Haller, S., Haacke, E. M., Thurnher, M. M., & Barkhof, F. (2021). Susceptibility-weighted Imaging: Technical Essentials and Clinical Neurologic Applications. *Radiology*, *299*(1), 3–26. https://doi.org/10.1148/radiol.2021203071

Hanson, H. R., Gittelman, M. A., & Pomerantz, W. J. (2019). Trends of ED visits, admissions, and deaths for pediatric traumatic brain injury comparing sport and non-sport mechanisms. *Injury Epidemiology*, *6*(S1), 23. https://doi.org/10.1186/s40621-019-0207-x

Hashemi, R. H. (2018). *MRI the basics* (4th ed.). Wolters Kluwer Health.

Hassan, N., Butler, C., DeCou, J., Crumb, T., Flohr, S., Reischman, D., & Junewick, J. (2020). Pediatric cervical spine injuries on CT: Difference in accuracy of interpretations by pediatric versus non-pediatric radiologists. *Emergency Radiology*, *27*(2), 185–190. https://doi.org/10.1007/s10140-019-01743-7

Henry, M. K., French, B., Feudtner, C., Zonfrillo, M. R., Lindberg, D. M., Anderst, J. D., Berger, R. P., & Wood, J. N. (2021). Cervical Spine Imaging and Injuries in Young Children With Non-Motor Vehicle Crash-Associated Traumatic Brain Injury. *Pediatric Emergency Care*, *37*(1), e1–e6. https://doi.org/10.1097/PEC.0000000000001455

Henry, M., Riesenburger, R. I., Kryzanski, J., Jea, A., & Hwang, S. W. (2013). A retrospective comparison of CT and MRI in detecting pediatric cervical spine injury. *Child's Nervous System*, *29*(8), 1333–1338. https://doi.org/10.1007/s00381-013-2092-x

Henry, M., Scarlata, K., Riesenburger, R. I., Kryzanski, J., Rideout, L., Samdani, A., Jea, A., & Hwang, S. W. (2013). Utility of STIR MRI in pediatric cervical spine clearance after trauma: Clinical article. *Journal of Neurosurgery: Pediatrics*, *12*(1), 30–36. https://doi.org/10.3171/2013.4.PEDS12477

Hoffman JR, Wolfson AB, Todd K, Mower WR, for the NEXUS Group. (1998). Selective cervical spine radiography in blunt trauma: Methodology of the National Emergency X-Radiography Utilization Study (NEXUS). *Annals of Emergency Medicine* 32, 461-469.

Holdsworth F. (1970). Review Article: Fractures, Dislocations and Fracture-Dislocations of the Spine. *The Journal of Bone & Joint Surgery*, 52(8), 1534–1551.

Holmes, J. F., & Akkinepalli, R. (2005). Computed Tomography Versus Plain Radiography to Screen for Cervical Spine Injury: A Meta-Analysis: *The Journal of Trauma: Injury, Infection, and Critical Care*, 58(5), 902–905. https://doi.org/10.1097/01.TA.0000162138.36519.2A

*ICRP* (2007). The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. *Annals of the ICRP* 37, 2-4. doi: 10.1016/j.icrp.2007.10.003

Igbinoba, Z., & Jaramillo, D. (2023). MR Imaging of the Developing Pediatric Marrow: An Overview of Pearls and Pitfalls. *Seminars in Musculoskeletal Radiology*, *27*(01), 022–029. https://doi.org/10.1055/s-0043-1762583

Jacob, R., Cox, M., Koral, K., Greenwell, C., Xi, Y., Vinson, L., Reeder, K., Weprin, B., Huang, R., & Booth, T. N. (2016). MR Imaging of the Cervical Spine in Nonaccidental Trauma: A Tertiary Institution Experience. *American Journal of Neuroradiology*, *37*(10), 1944–1950. https://doi.org/10.3174/ajnr.A4817

Jaimes, C., Chauvin, N. A., Delgado, J., & Jaramillo, D. (2014). MR Imaging of Normal Epiphyseal Development and Common Epiphyseal Disorders. *RadioGraphics*, *34*(2), 449–471. https://doi.org/10.1148/rg.342135070

Jaimes, C., Murcia, D. J., Miguel, K., DeFuria, C., Sagar, P., & Gee, M. S. (2018). Identification of quality improvement areas in pediatric MRI from analysis of patient safety reports. *Pediatric Radiology*, *48*(1), 66–73. https://doi.org/10.1007/s00247-017-3989-4

Jazayeri, S. B., Kankam, S. B., Golestani, A., Shobeiri, P., Gholami, M., Dabbagh Ohadi, M. A., Maroufi, S. F., Fattahi, M. R., Malekzadeh, H., Jazayeri, S. B., Ghodsi, Z., Ghodsi, S. M., & Rahimi-Movaghar, V. (2023). A systematic review and meta-analysis of the global epidemiology of pediatric traumatic spinal cord injuries. *European Journal of Pediatrics*, *182*(12), 5245–5257. https://doi.org/10.1007/s00431-023-05185-9

Junewick, J. J., Borders, H. L., & Davis, A. T. (2014). Pediatric Thoracic Spine Injuries: A Single-Institution Experience. *American Journal of Roentgenology*, *203*(3), 649–655. https://doi.org/10.2214/AJR.13.12143

Kadom, N., Khademian, Z., Vezina, G., Shalaby-Rana, E., Rice, A., & Hinds, T. (2014). Usefulness of MRI detection of cervical spine and brain injuries in the evaluation of abusive head trauma. *Pediatric Radiology*, *44*(7), 839–848. https://doi.org/10.1007/s00247-014-2874-7

Kadom, N., Palasis, S., Pruthi, S., Biffl, W. L., Booth, T. N., Desai, N. K., Falcone, R. A., Jones, J. Y., Joseph, M. M., Kulkarni, A. V., Marin, J. R., Milla, S. S., Mirsky, D. M., Myseros, J. S., Reitman, C., Robertson, R. L., Ryan, M. E., Saigal, G., Schulz, J., … Karmazyn, B. (2019). ACR Appropriateness Criteria® Suspected Spine Trauma-Child. *Journal of the American College of Radiology*, *16*(5), S286–S299. https://doi.org/10.1016/j.jacr.2019.02.003

Kaniewska, M., Kuhn, D., Deininger-Czermak, E., Wolharn, L., Finkenstaedt, T., & Guggenberger, R. (2023). 3D zero-echo time and 3D T1-weighted gradient-echo MRI sequences as an alternative to CT for the evaluation of the lumbar facet joints and lumbosacral transitional vertebrae. *Acta Radiologica*, *64*(6), 2137–2144. https://doi.org/10.1177/02841851231165487

Karmazyn, B., Reher, T. A., Supakul, N., Streicher, D. A., Kiros, N., Diggins, N., Jennings, S. G., Eckert, G. J., Hibbard, R. A., & Radhakrishnan, R. (2022). Whole-Spine MRI in Children With Suspected Abusive Head Trauma. *American Journal of Roentgenology*, *218*(6), 1074–1087. https://doi.org/10.2214/AJR.21.26674

Kim, Y. D., Park, H. K., Chang, J. C., Choi S. K. (2004). Thoracic Spinal Cord Injury without Radiographic Abnormality Following Minor Trauma in Adult. *Journal of Korean Neurosurgical Society.* 36, 405–407.

Kjaer, P., Leboeuf-Yde, C., Sorensen, J. S., & Bendix, T. (2005). An Epidemiologic Study of MRI and Low Back Pain in 13-Year-Old Children. *SPINE*, 30(7), 798–806. 10.1097/01.brs.0000157424.72598.ec

Klein, J., Pohl, J., Vinson, E. N., Brant, W. E., & Helms, C. A. (2018). *Brant and Helms' Fundamentals of Diagnostic Radiology* (5th ed.). Wolters Kluwer.

Kohler, R., Vargas, M. I., Masterson, K., Lovblad, K. O., Pereira, V. M., & Becker, M. (2011). CT and MR Angiography Features of Traumatic Vascular Injuries of the Neck. *American Journal of Roentgenology*, *196*(6), W800–W809. https://doi.org/10.2214/AJR.10.5735

Konovalov, N., Peev, N., Zileli, M., Sharif, S., Kaprovoy, S., & Timonin, S. (2020). Pediatric Cervical Spine Injuries and SCIWORA: WFNS Spine Committee Recommendations. *Neurospine*, *17*(4), 797–808. https://doi.org/10.14245/ns.2040404.202

Kuitunen, I., Ponkilainen, V. T., Iverson, G. L., Isokuortti, H., Luoto, T. M., & Mattila, V. M. (2023). Increasing incidence of pediatric mild traumatic brain injury in Finland – a nationwide register study from 1998 to 2018. *Injury*, *54*(2), 540–546. https://doi.org/10.1016/j.injury.2022.12.023

Kumar, Y., & Hayashi, D. (2016). Role of magnetic resonance imaging in acute spinal trauma: A pictorial review. *BMC Musculoskeletal Disorders*, *17*(1), 310. https://doi.org/10.1186/s12891-016-1169-6

Lawson, J. P., Ogden, J. A., Bucholz, R. W., & Hughes, S. A. (1987). Physeal injuries of the cervical spine. *Journal of Pediatric Orthopedics*, *7*(4), 428–435. https://doi.org/10.1097/01241398-198707000-00010

Le, T. V., Baaj, A. A., Deukmedjian, A., Uribe, J. S., & Vale, F. L. (2011). Chance fractures in the pediatric population: A review. *Journal of Neurosurgery: Pediatrics*, *8*(2), 189–197. https://doi.org/10.3171/2011.5.PEDS10538

Lee, L. K., Porter, J. J., Mannix, R., Rees, C. A., Schutzman, S. A., Fleegler, E. W., & Farrell, C. A. (2022). Pediatric Traumatic Injury Emergency Department Visits and Management in US Children's Hospitals From 2010 to 2019. *Annals of Emergency Medicine*, *79*(3), 279–287. https://doi.org/10.1016/j.annemergmed.2021.10.008

Lee, R. P., Zhou, N. J., Hidalgo, J., Titsworth, W. L., Uribe-Cardenas, R., Chowdhury, R., Chun, Y., Nasr, I., Stewart, F. D., Sponseller, P., Groves, M. L., & Jackson, E. M. (2022). Weighing the risk profile of cervical spine MRI in evaluating pediatric cervical spine injuries. *Pediatric Neurosurgery*. https://doi.org/10.1159/000525863

Leonard, J. C., Kuppermann, N., Olsen, C., Babcock-Cimpello, L., Brown, K., Mahajan, P., Adelgais, K. M., Anders, J., Borgialli, D., Donoghue, A., Hoyle, J. D., Kim, E., Leonard, J. R., Lillis, K. A., Nigrovic, L. E., Powell, E. C., Rebella, G., Reeves, S. D., Rogers, A. J., … Jaffe, D. M. (2011). Factors Associated With Cervical Spine Injury in Children After Blunt Trauma. *Annals of Emergency Medicine*, *58*(2), 145–155. https://doi.org/10.1016/j.annemergmed.2010.08.038

Leonard, J. R., Jaffe, D. M., Kuppermann, N., Olsen, C. S., & Leonard, J. C. (2014). Cervical Spine Injury Patterns in Children. *Pediatrics*, *133*(5), e1179–e1188. https://doi.org/10.1542/peds.2013-3505

Lerwick, J. L. (2016). Minimizing pediatric healthcare-induced anxiety and trauma. *World Journal of Clinical Pediatrics*, *5*(2), 143. https://doi.org/10.5409/wjcp.v5.i2.143

Lévy, C., Laissy, J. P., Raveau, V., Amarenco, P., Servois, V., Bousser, M. G., & Tubiana, J. M. (1994). Carotid and vertebral artery dissections: Three-dimensional time-of-flight MR angiography and

MR imaging versus conventional angiography. *Radiology*. https://doi.org/10.1148/radiology.190.1.8259436

Lisanti, C., Carlin, C., Banks, K. P., & Wang, D. (2007). Normal MRI Appearance and Motion-Related Phenomena of CSF. *American Journal of Roentgenology*, *188*(3), 716–725. https://doi.org/10.2214/AJR.05.0003

Lo, C., Ormond, G., Mcdougall, R., Sheppard, S. J., & Davidson, A. J. (2014). Effect of Magnetic Resonance Imaging on Core Body Temperature in Anaesthetised Children. *Anaesthesia and Intensive Care*, *42*(3), 333–339. https://doi.org/10.1177/0310057X1404200310

Luehmann, N. C., Pastewski, J. M., Cirino, J. A., Al-Hadidi, A., DeMare, A. M., Riggs, T. W., Novotny, N. M., & Akay, B. (2020). Implementation of a pediatric trauma cervical spine clearance pathway. *Pediatric Surgery International*, *36*(1), 93–101. https://doi.org/10.1007/s00383-019-04544-8

Lund, T., Schlenzka, D., Lohman, M., Ristolainen, L., Kautiainen, H., Klemetti, E., & Österman, K. (2022). The intervertebral disc during growth: Signal intensity changes on magnetic resonance imaging and their relevance to low back pain. *PLOS ONE*, *17*(10), e0275315. https://doi.org/10.1371/journal.pone.0275315

Madura, C. J., & Johnston, J. M. (2017). Classification and Management of Pediatric Subaxial Cervical Spine Injuries. *Neurosurgery Clinics of North America*, *28*(1), 91–102. https://doi.org/10.1016/j.nec.2016.07.004

Marin, J. R., Rodean, J., Hall, M., Alpern, E. R., Aronson, P. L., Chaudhari, P. P., Cohen, E., Freedman, S. B., Morse, R. B., Peltz, A., Samuels-Kalow, M., Shah, S. S., Simon, H. K., & Neuman, M. I. (2020). Trends in Use of Advanced Imaging in Pediatric Emergency Departments, 2009-2018. *JAMA Pediatrics*, *174*(9), e202209. https://doi.org/10.1001/jamapediatrics.2020.2209

McAllister, A. S., Nagaraj, U., & Radhakrishnan, R. (2019). Emergent Imaging of Pediatric Cervical Spine Trauma. *RadioGraphics*, *39*(4), 1126–1142. https://doi.org/10.1148/rg.2019180100

Mendelsohn, D. B., Zollars, L., Weatherall, P. T., & Girson, M. (1990). MR of Cord Transaction. *Journal of Computer Assisted Tomography*, *14*(6), 909.

Miglioretti, D. L., Johnson, E., Williams, A., Greenlee, R. T., Weinmann, S., Solberg, L. I., Feigelson, H. S., Roblin, D., Flynn, M. J., Vanneman, N., & Smith-Bindman, R. (2013). *The Use of Computed Tomography in Pediatrics and the Associated Radiation Exposure and Estimated Cancer Risk*, 167(8), 700–707. doi:10.1001/jamapediatrics.2013.311

Mistry, D., Munjal, H., Ellika, S., & Chaturvedi, A. (2022). Pediatric spine trauma: A comprehensive review. *Clinical Imaging*, *87*, 61–76. https://doi.org/10.1016/j.clinimag.2022.04.012

Mo, A. Z., Miller, P. E., Pizones, J., Helenius, I., Ruf, M., El-Hawary, R., de Oliveira, R. G., Ovadia, D., Kawakami, N., Crawford, H., Odent, T., Yazici, M., Johnson, M. B., Miyanji, F., & Hedequist, D. J. (2021). The reliability of the AOSpine Thoracolumbar Spine Injury Classification System in children: An international validation study. *Journal of Children's Orthopaedics*, *15*(5), 472–478. https://doi.org/10.1302/1863-2548.15.200188

Mo, A. Z., Miller, P. E., Troy, M. J., Rademacher, E. S., & Hedequist, D. J. (2019). The AOSpine thoracolumbar spine injury classification system: A comparative study with the thoracolumbar injury classification system and severity score in children. *OTA International: The Open Access Journal of Orthopaedic Trauma*, *2*(4), e036. https://doi.org/10.1097/OI9.0000000000000036

Modic, M., Weinstein, M., Pavlicek, W., Boumphrey, F., Starnes, D., & Duchesneau, P. (1983). Magnetic resonance imaging of the cervical spine: Technical and clinical observations. *American Journal of Roentgenology*, 141(6), 1129–1136.

Modic, M. T., Weinstein, M. A., Pavlicek, W., Starnes, D. L., Duchesneau, P. M., Boumphrey, F., & Hardy, R. J. (1983). Nuclear magnetic resonance imaging of the spine. *Radiology*, *148*(3), 757–762. https://doi.org/10.1148/radiology.148.3.6878697

Mohseni, S., Talving, P., Branco, B. C., Chan, L. S., Lustenberger, T., Inaba, K., Bass, M., & Demetriades, D. (2011). Effect of age on cervical spine injury in pediatric population: A National Trauma Data Bank review. *Journal of Pediatric Surgery*, *46*(9), 1771–1776. https://doi.org/10.1016/j.jpedsurg.2011.03.007

Moore, J. M., Hall, J., Ditchfield, M., Xenos, C., & Danks, A. (2017). Utility of plain radiographs and MRI in cervical spine clearance in symptomatic non-obtunded pediatric patients without high-impact trauma. *Child's Nervous System*, *33*(2), 249–258. https://doi.org/10.1007/s00381-016-3273-1

Murphy, R. F., Davidson, A. R., Kelly, D. M., Warner, W. C., & Sawyer, J. R. (2015). Subaxial Cervical Spine Injuries in Children and Adolescents. *Journal of Pediatric Orthopaedics*, *35*(2), 136–139. https://doi.org/10.1097/BPO.0000000000000341

Nagayama, Y., Oda, S., Nakaura, T., Tsuji, A., Urata, J., Furusawa, M., Utsunomiya, D., Funama, Y., Kidoh, M., & Yamashita, Y. (2018). Radiation Dose Reduction at Pediatric CT: Use of Low Tube Voltage and Iterative Reconstruction. *RadioGraphics*, *38*(5), 1421–1440. https://doi.org/10.1148/rg.2018180041

Nagpal, P., Policeni, B. A., Bathla, G., Khandelwal, A., Derdeyn, C., & Skeete, D. (2018). Blunt Cerebrovascular Injuries: Advances in Screening, Imaging, and Management Trends. *American Journal of Neuroradiology*, *39*(3), 406–414. https://doi.org/10.3174/ajnr.A5412

Nidecker, A., & Shen, P. (2016). Magnetic Resonance Imaging of the Craniovertebral Junction Ligaments: Normal Anatomy and Traumatic Injury. *Journal of Neurological Surgery Part B: Skull Base*, *77*(05), 388–395. https://doi.org/10.1055/s-0036-1584230

Nigrovic, L. E., Rogers, A. J., Adelgais, K. M., Olsen, C. S., Leonard, J. R., Jaffe, D. M., & Leonard, J. C. (2012). Utility of Plain Radiographs in Detecting Traumatic Injuries of the Cervical Spine in Children: *Pediatric Emergency Care*, *28*(5), 426–432. https://doi.org/10.1097/PEC.0b013e3182531911

Ofer, A., Nitecki, S. S., Braun, J., Daitzchman, M., Goldsher, D., Hoffman, A., & Engel, A. (2001). CT Angiography of the Carotid Arteries in Trauma to the Neck. *European Journal of Vascular and Endovascular Surgery*, *21*(5), 401–407. https://doi.org/10.1053/ejvs.2001.1330

O'Neill, C., Wenzel, A., Walterscheid, Z., & Carmouche, J. (2021). Distinguishing Pseudosubluxation From True Injury: A Case of C2-3 and C3-4 Subluxation in a Pediatric Patient. *JAAOS: Global Research and Reviews*, *5*(12). https://doi.org/10.5435/JAAOSGlobal-D-20-00238

Paajanen, H., Erkintalo, M., Parkkola, R., Salminen, J., & Kormano, M. (1997). Age-dependent correlation of low-back pain and lumbar disc degeneration. *Archives of orthopaedic and trauma surgery*, *116*(1-2), 106–107. 10.1007/BF00434112.

Pang, D., & Wilberger, J. E., Jr. (1982). Spinal cord injury without radiographic abnormalities in children. *Journal of Neurosurgery*, 57(1), 114-129. 10.3171/jns.1982.57.1.0114

Pang, D. (2004). Spinal Cord Injury without Radiographic Abnormality in Children, 2 Decades Later. *Neurosurgery*, *55*(6), 1325–1343. https://doi.org/10.1227/01.NEU.0000143030.85589.E6

Peschke, E., Ulloa, P., Jansen, O., & Hoevener, J.-B. (2021). Metallic Implants in MRI – Hazards and Imaging Artifacts. *RöFo - Fortschritte Auf Dem Gebiet Der Röntgenstrahlen Und Der Bildgebenden Verfahren*, *193*(11), 1285–1293. https://doi.org/10.1055/a-1460-8566

Phillips, N., Rasmussen, K., McGuire, S., Abel, K.-A., Acworth, J., Askin, G., Brady, R., Walsh, M., & Babl, F. E. (2021). Projected paediatric cervical spine imaging rates with application of NEXUS, Canadian C-Spine and PECARN clinical decision rules in a prospective Australian cohort. *Emergency Medicine Journal*, *38*(5), 330–337. https://doi.org/10.1136/emermed-2020-210325

Piatt, J., & Imperato, N. (2018). Epidemiology of spinal injury in childhood and adolescence in the United States: 1997–2012. *Journal of Neurosurgery: Pediatrics*, *21*(5), 441–448. https://doi.org/10.3171/2017.10.PEDS17530

Platzer, P., Jaindl, M., Thalhammer, G., Dittrich, S., Kutscha-Lissberg, F., Vecsei, V., & Gaebler, C. (2007). Cervical Spine Injuries in Pediatric Patients. *Journal of Trauma: Injury, Infection & Critical Care*, *62*(2), 389–396. https://doi.org/10.1097/01.ta.0000221802.83549.46

Pouw, M. H., Van Der Vliet, A. M., Van Kampen, A., Thurnher, M. M., Van De Meent, H., & Hosman, A. J. F. (2012). Diffusion-weighted MR imaging within 24 h post-injury after traumatic spinal cord injury: A qualitative meta-analysis between T2-weighted imaging and diffusion-weighted MR imaging in 18 patients. *Spinal Cord*, *50*(6), 426–431. https://doi.org/10.1038/sc.2011.168

Preston, D. L., Ron, E., Tokuoka, S., Funamoto, S., Nishi, N., Soda, M., Mabuchi, K., & Kodama, K. (2007). Solid Cancer Incidence in Atomic Bomb Survivors: 1958–1998. *Radiation Research*, *168*(1), 1–64. https://doi.org/10.1667/RR0763.1

Puisto, V., Kääriäinen, S., Impinen, A., Parkkila, T., Vartiainen, E., Jalanko, T., Pakarinen, M. P., & Helenius, I. (2010). Incidence of Spinal and Spinal Cord Injuries and Their Surgical Treatment in Children and Adolescents: A Population-Based Study. *SPINE*, *35*(1), 104–107. https://doi.org/10.1097/BRS.0b013e3181c64423

Qaiyum, M., Tyrrell, P. N. M., McCall, I. W., & Cassar-Pullicino, V. N. (2001). MRI detection of unsuspected vertebral injury in acute spinal trauma: Incidence and significance. *Skeletal Radiology*, *30*(6), 299–304. https://doi.org/10.1007/s002560100329

Qualls, D., Leonard, J. R., Keller, M., Pineda, J., & Leonard, J. C. (2015). Utility of magnetic resonance imaging in diagnosing cervical spine injury in children with severe traumatic brain injury. *Journal of Trauma and Acute Care Surgery*, *78*(6), 1122–1128. https://doi.org/10.1097/TA.0000000000000646

Riascos, R., Bonfante, E., Cotes, C., Guirguis, M., Hakimelahi, R., & West, C. (2015). Imaging of Atlanto-Occipital and Atlantoaxial Traumatic Injuries: What the Radiologist Needs to Know. *RadioGraphics*, *35*(7), 2121–2134. https://doi.org/10.1148/rg.2015150035

Roche, S., Crombé, A., Benhamed, A., Hak, J.-F., Dabadie, A., Fauconnier-Fatus, C., Rega, A., Pech-Gourg, G., Tazarourte, K., Seux, M., Acquier, A., & Gorincour, G. (2023). Risk Factors Associated with Traumatic Brain Injury and Implementation of Guidelines for Requesting Computed Tomography After Head Trauma Among Children in France. *JAMA Network Open*, *6*(5), e2311092. https://doi.org/10.1001/jamanetworkopen.2023.11092

Rozzelle, C. J., Aarabi, B., Dhall, S. S., Gelb, D. E., Hurlbert, R. J., Ryken, T. C., Theodore, N., Walters, B. C., & Hadley, M. N. (2013). Management of Pediatric Cervical Spine and Spinal Cord Injuries. *Neurosurgery*, *72*(supplement 2), 205–226. https://doi.org/10.1227/NEU.0b013e318277096c

Runge, S. B., Christensen, N. L., Jensen, K., & Jensen, I. E. (2018). Children centered care: Minimizing the need for anesthesia with a multi-faceted concept for MRI in children aged 4–6. *European Journal of Radiology*, *107*, 183–187. https://doi.org/10.1016/j.ejrad.2018.08.026

Rutman, A. M., Vranic, J. E., & Mossa-Basha, M. (2018). Imaging and Management of Blunt Cerebrovascular Injury. *RadioGraphics*, *38*(2), 542–563. https://doi.org/10.1148/rg.2018170140

Sacks, B., Meyerson, G., & Siegel, J. A. (2016). Epidemiology Without Biology: False Paradigms, Unfounded Assumptions, and Specious Statistics in Radiation Science (with Commentaries by Inge Schmitz-Feuerhake and Christopher Busby and a Reply by the Authors). *Biological Theory*, *11*(2), 69–101. https://doi.org/10.1007/s13752-016-0244-4

Samei, E., & Peck, D. J. (2019). *Hendee's Physics of Medical Imaging*. John Wiley & Sons, Incorporated.

Saul, D., & Dresing, K. (2018). Epidemiology of Vertebral Fractures in Pediatric and Adolescent Patients. *Pediatric Reports*, *10*(1), 7232. https://doi.org/10.4081/pr.2018.7232

Schmitt, W. G., & Rücker, H. C. (1979). [Long-term follow-up of stress injuries to the metaphyses and apophyses of the spinous processes of juvenile thoracic spines (Schmitt's disease) (author's transl)]. *RoFo: Fortschritte Auf Dem Gebiete Der Rontgenstrahlen Und Der Nuklearmedizin*, *131*(6), 623–631. https://doi.org/10.1055/s-0029-1231505

Schoenfeld, A. J., Bono, C. M., McGuire, K. J., Warholic, N., & Harris, M. B. (2010). Computed Tomography Alone Versus Computed Tomography and Magnetic Resonance Imaging in the Identification of Occult Injuries to the Cervical Spine: A Meta-Analysis. *Journal of Trauma: Injury, Infection & Critical Care*, *68*(1), 109–114. https://doi.org/10.1097/TA.0b013e3181c0b67a

Sellin, J. N., Steele, W. J., Simpson, L., Huff, W. X., Lane, B. C., Chern, J. J., Fulkerson, D. H., Sayama, C. M., & Jea, A. (2016). Multicenter retrospective evaluation of the validity of the Thoracolumbar Injury Classification and Severity Score system in children. *Journal of Neurosurgery: Pediatrics*, *18*(2), 164–170. https://doi.org/10.3171/2016.1.PEDS15663

Sethi, M. K., Schoenfeld, A. J., Bono, C. M., & Harris, M. B. (2009). The evolution of thoracolumbar injury classification systems. *The Spine Journal*, *9*(9), 780–788. https://doi.org/10.1016/j.spinee.2009.04.003

Shanmuganathan, K., Zhuo, J., Bodanapally, U. K., Kuladeep, S., Aarabi, B., Adams, J., Miller, C., Gullapallie, R. P., & Menakar, J. (2020). Comparison of Acute Diffusion Tensor Imaging and Conventional Magnetic Resonance Parameters in Predicting Long-Term Outcome after Blunt Cervical Spinal Cord Injury. *Journal of Neurotrauma*, *37*(3), 458–465. https://doi.org/10.1089/neu.2019.6394

Shaw, M., Burnett, H., Wilson, A., & Chan, O. (1999). Pseudosubluxation of C2 on C3 in Polytraumatized Children—Prevalence and Significance. *Clinical Radiology*, *54*(6), 377–380. https://doi.org/10.1053/crad.1999.0192

Shen, H., Tang, Y., Huang, L., Yang, R., Wu, Y., Wang, P., Shi, Y., He, X., Liu, H., & Ye, J. (2007). Applications of diffusion-weighted MRI in thoracic spinal cord injury without radiographic abnormality. *International Orthopaedics*, *31*(3), 375–383. https://doi.org/10.1007/s00264-006-0175-y

Shin, J. I., Lee, N. J., & Cho, S. K. (2016). Pediatric Cervical Spine and Spinal Cord Injury: A National Database Study. *SPINE*, *41*(4), 283–292. https://doi.org/10.1097/BRS.0000000000001176

Siegel, J. A., Pennington, C. W., & Sacks, B. (2017). Subjecting Radiologic Imaging to the Linear No-Threshold Hypothesis: A Non Sequitur of Non-Trivial Proportion. *Journal of Nuclear Medicine*, *58*(1), 1–6. https://doi.org/10.2967/jnumed.116.180182

Siegel, J. A., Sacks, B., Pennington, C. W., & Welsh, J. S. (2017). Dose Optimization to Minimize Radiation Risk for Children Undergoing CT and Nuclear Medicine Imaging Is Misguided and Detrimental. *Journal of Nuclear Medicine*, *58*(6), 865–868. https://doi.org/10.2967/jnumed.117.195263

Singer, G., Parzer, S., Castellani, C., Wegmann, H., Lindbichler, F., Till, H., & Eberl, R. (2016). The influence of brace immobilization on the remodeling potential of thoracolumbar impaction fractures in children and adolescents. *European Spine Journal*, *25*(2), 607–613. https://doi.org/10.1007/s00586-015-4250-1

Singh, D., Monga, A., De Moura, H. L., Zhang, X., Zibetti, M. V. W., & Regatte, R. R. (2023). Emerging Trends in Fast MRI Using Deep-Learning Reconstruction on Undersampled k-Space Data: A Systematic Review. *Bioengineering*, *10*(9), 1012. https://doi.org/10.3390/bioengineering10091012

Sires, J., Ovenden, C., Antoniou, G., Robinson, N., & Williams, N. (2022). An audit of computed tomography request practices for suspected cervical spine injury post-guideline change in a tertiary referral paediatric hospital. *ANZ Journal of Surgery*, *92*(1–2), 180–187. https://doi.org/10.1111/ans.17183

Slaar, A., Fockens, M. M., Wang, J., Maas, M., Wilson, D. J., Goslings, J. C., Schep, N. W., & van Rijn, R. R. (2017). Triage tools for detecting cervical spine injury in pediatric trauma patients. *Cochrane Database of Systematic Reviews*, *2017*(12). https://doi.org/10.1002/14651858.CD011686.pub2

Smith-Bindman, R., Lipson, J., Marcus, R., Kim, K.-P., Mahesh, M., & Gould, R. (2009). Radiation Dose Associated With Common Computed Tomography Examinations and the Associated Lifetime Attributable Risk of Cancer. *ARCH INTERN MED*, *169*(22).

Snyder, E. J., Zhang, W., Jasmin, K. C., Thankachan, S., & Donnelly, L. F. (2018). Gauging potential risk for patients in pediatric radiology by review of over 2,000 incident reports. *Pediatric Radiology*, *48*(13), 1867–1874. https://doi.org/10.1007/s00247-018-4238-1

So, T. Y., Sawhney, A., Wang, L., & Wang, Y. X. J. (2022). Current Concepts in Imaging Diagnosis and Screening of Blunt Cerebrovascular Injuries. *Tomography*, 8(1), 402–413. https://doi.org/10.3390/tomography8010033

Sodickson, A., Baeyens, P. F., Andriole, K. P., Prevedello, L. M., Nawfel, R. D., Hanson, R., & Khorasani, R. (2009). Recurrent CT, Cumulative Radiation Exposure, and Associated Radiation-induced Cancer Risks from CT of Adults. *Radiology*, *251*(1), 175–184. https://doi.org/10.1148/radiol.2511081296

Soldatos, T., Andreisek, G., Thawait, G. K., Guggenberger, R., Williams, E. H., Carrino, J. A., & Chhabra, A. (2013). High-Resolution 3-T MR Neurography of the Lumbosacral Plexus. *RadioGraphics*, *33*(4), 967–987. https://doi.org/10.1148/rg.334115761

Spampinato, M. V., Chetta, J. A., Adcock, C., Kocher, M., Truitt, A., Lydon, G., Eskandari, R., & Yazdani, M. (2023). Non-sedated fast spine magnetic resonance imaging in pediatric patients. *Pediatric Radiology*, *53*(12), 2478–2489. https://doi.org/10.1007/s00247-023-05760-0

Steffensen, C., Trypis, G., Mander, G. T. W., & Munn, Z. (2021). Optimisation of radiographic acquisition parameters for direct digital radiography: A systematic review. *Radiography*, *27*(2), 663–672. https://doi.org/10.1016/j.radi.2020.08.012

Steinmetz, M. P., Mroz, T. E., & Benzel, E. C. (2010). Craniovertebral Junction: Biomechanical Considerations. *Neurosurgery*, *66*(3), A7–A12. https://doi.org/10.1227/01.NEU.0000366109.85796.42

Stephenson, K. J., Bullard, K. L., Wyrick, D. L., Ramakrishnaiah, R. H., Albert, G. W., & Maxson, R. T. (2023). Can you see with CT? Is cervical spine computed tomographic imaging sufficient in pediatric trauma? *The American Journal of Surgery*, *226*(1), 122–127. https://doi.org/10.1016/j.amjsurg.2023.03.001

Stiell, I. G., Wells, G. A., Vandemheen, K. L., Clement, C. M., Lesiuk, H., Maio, V. J. D., Laupacis, A., Schull, M., McKnight, R. D., Verbeek, R., Brison, R., Cass, D., Dreyer, J., Eisenhauer, M. A., Greenberg, G. H., MacPhail, I., Morrison, L., Reardon, M., & Worthington, J. (2001). The Canadian C-Spine Rule for Radiography in Alert and Stable Trauma Patients. *JAMA*, 286(15), 1841–1848. doi:10.1001/jama.286.15.1841

Swischuk, L. E. (1977). Anterior Displacement of C2 in Children: Physiologic or Pathologic? *Radiology*, 122(3), 759–763. doi: 10.1148/122.3.759

Swischuk, L. E., Swischuk, P. N., & John, S. D. (1993). Wedging of C-3 in infants and children: Usually a normal finding and not a fracture. *Radiology*, *188*(2), 523–526. https://doi.org/10.1148/radiology.188.2.8327708

Talbott, J. F., Huie, J. R., Ferguson, A. R., Bresnahan, J. C., Beattie, M. S., & Dhall, S. S. (2019). MR Imaging for Assessing Injury Severity and Prognosis in Acute Traumatic Spinal Cord Injury. *Radiologic Clinics of North America*, *57*(2), 319–339. https://doi.org/10.1016/j.rcl.2018.09.004

Talbott, J. F., Whetstone, W. D., Readdy, W. J., Ferguson, A. R., Bresnahan, J. C., Saigal, R., Hawryluk, G. W. J., Beattie, M. S., Mabray, M. C., Pan, J. Z., Manley, G. T., & Dhall, S. S. (2015). The Brain and Spinal Injury Center score: A novel, simple, and reproducible method for assessing the severity of acute cervical spinal cord injury with axial T2-weighted MRI findings. *Journal of Neurosurgery: Spine*, *23*(4), 495–504. https://doi.org/10.3171/2015.1.SPINE141033

Ten Brinke, J. G., Slinger, G., Slaar, A., Saltzherr, T. P., Hogervorst, M., & Goslings, J. C. (2021). Increased and unjustified CT usage in paediatric C-spine clearance in a level 2 trauma centre. *European Journal of Trauma and Emergency Surgery*, *47*(3), 781–789. https://doi.org/10.1007/s00068-020-01520-z

The Royal College of Radiologists. (2014) Paediatric trauma protocols. *London: The Royal College of Radiologists*. https://www.rcr.ac.uk/our-services/all-our-publications/clinical-radiology-publications/paediatric-trauma-protocols/

Thestrup, J., Hybschmann, J., Madsen, T. W., Bork, N. E., Sørensen, J. L., Afshari, A., Borgwardt, L., Berntsen, M., Born, A. P., Aunsholt, L., Larsen, V. A., & Gjærde, L. K. (2023). Nonpharmacological Interventions to Reduce Sedation and General Anesthesia in Pediatric MRI: A Meta-analysis. *Hospital Pediatrics*, *13*(10), e301–e313. https://doi.org/10.1542/hpeds.2023-007289

Tofte, J. N., CarlLee, T. L., Holte, A. J., Sitton, S. E., & Weinstein, S. L. (2017). Imaging Pediatric Spondylolysis: A Systematic Review. *SPINE*, 15;42(10), 777-782. doi: 10.1097/BRS.0000000000001912.

Tong, G. E., Staudenmayer, K., Lin, F., & Hsia, R. Y. (2016). Use of emergency department imaging in patients with minor trauma. *Journal of Surgical Research*, *203*(1), 238–245. https://doi.org/10.1016/j.jss.2015.11.046

Vaccaro, A. R., Koerner, J. D., Radcliff, K. E., Oner, F. C., Reinhold, M., Schnake, K. J., Kandziora, F., Fehlings, M. G., Dvorak, M. F., Aarabi, B., Rajasekaran, S., Schroeder, G. D., Kepler, C. K., & Vialle, L. R. (2016). AOSpine subaxial cervical spine injury classification system. *European Spine Journal*, *25*(7), 2173–2184. https://doi.org/10.1007/s00586-015-3831-3

Vaccaro, A. R., Lehman, R. A., Hurlbert, R. J., Anderson, P. A., Harris, M., Hedlund, R., Harrop, J., Dvorak, M., Wood, K., Fehlings, M. G., Fisher, C., Zeiller, S. C., Anderson, D. G., Bono, C. M., Stock, G. H., Brown, A. K., & Kuklo, T. (2005). A New Classification of Thoracolumbar Injuries. *SPINE*, 30(20), 2325–2333. doi: 10.1097/01.brs.0000182986.43345.cb

Vander Have, K.L., Caird M. S., Gross S., Farley F., Graziano G. A., Stauff M., & Segal L. S. (2009). Burst Fractures of the Thoracic and Lumbar Spine in Children and Adolescents. *Journal of Pediatric Orthopaedics*, 29(7), 713–719. doi: 10.1097/BPO.0b013e3181b76a44

Volavc, T. S., & Rupreht, M. (2021). MRI of the Morel-Lavallée lesion – a case series. *Radiology and Oncology*, *55*(3), 268–273. https://doi.org/10.2478/raon-2021-0018

Vranic, J. E., Huynh, T. J., Fata, P., Barber, J., Bonow, R. H., Levitt, M. R., Temkin, N., Morton, R., Kelly, C., Shibata, D. K., & Mossa-Basha, M. (2020). The ability of magnetic resonance black blood vessel wall imaging to evaluate blunt cerebrovascular injury following acute trauma. *Journal of Neuroradiology*, *47*(3), 210–215. https://doi.org/10.1016/j.neurad.2019.01.091

Wang, M., Dai, Y., Han, Y., Haacke, E. M., Dai, J., & Shi, D. (2011). Susceptibility weighted imaging in detecting hemorrhage in acute cervical spinal cord injury. *Magnetic Resonance Imaging*, *29*(3), 365–373. https://doi.org/10.1016/j.mri.2010.10.016

Wiesinger, F., & Ho, M.-L. (2022). Zero-TE MRI: Principles and applications in the head and neck. *The British Journal of Radiology*, *95*(1136), 20220059. https://doi.org/10.1259/bjr.20220059

Woo, T. D., Tony, G., Charran, A., Lalam, R., Singh, J., Tyrrell, P. N. M., & Cassar-Pullicino, V. N. (2018). Radiographic morphology of normal ring apophyses in the immature cervical spine. *Skeletal Radiology*, *47*(9), 1221–1228. https://doi.org/10.1007/s00256-018-2909-5

Yamaguchi, K. T., Myung, K. S., Alonso, M. A., & Skaggs, D. L. (2012). Clay-Shoveler's Fracture Equivalent in Children. *SPINE*, *37*(26), E1672–E1675. https://doi.org/10.1097/BRS.0b013e318273e191

Yamaguchi, K. T., Skaggs, D. L., Acevedo, D. C., Myung, K. S., Choi, P., & Andras, L. (2012). Spondylolysis is frequently missed by MRI in adolescents with back pain. *Journal of Children's Orthopaedics*, *6*(3), 237–240. https://doi.org/10.1007/s11832-012-0409-z

Yin, B., Tang, Y., Ye, J., Wu, Y., Wang, P., Huang, L., Yang, R., & Shen, H. (2010). Sensitivity and specificity of in vivo diffusion-weighted MRI in acute spinal cord injury. *Journal of Clinical Neuroscience*, *17*(9), 1173–1179. https://doi.org/10.1016/j.jocn.2010.02.020

Zink, F. E. (1997). X-ray tubes. *RadioGraphics*, *17*(5), 1259–1268. https://doi.org/10.1148/radiographics.17.5.9308113

Zou, Z., Teng, A., Huang, L., Luo, X., Wu, X., Zhang, H., & Chen, K. (2021). Pediatric Spinal Cord Injury without Radiographic Abnormality: The Beijing Experience. *Spine*, *46*(20), E1083–E1088. https://doi.org/10.1097/BRS.0000000000004030

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