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Review

Imaging of cervical spine traumas

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ABSTRACT

Spinal traumas represent a significant proportion of muscle-skeletal injuries worldwide.

Spinal injuries involve a complex structure with components having different traumatic susceptibility and variable healing capabilities.

The interaction of numerous variables at time of trauma creates a great variety of lesions which makes challenging the creation and comparison of homogeneous groups, with difficulties in classifying spinal lesions, in assessing their instability, and in defining the indication and outcome of different treatment strategies.

The evolution of concepts on instability has accompanied that of traumas classification schemes and treatment strategies. The assessment of instability in a spinal injury is actually crucial in front of newer surgical techniques and hardwares.

Despite a long history of attempts to classify spinal traumas, it remains some degree of controversy in describing imaging data and a wide variety of treatment strategies.

Acute cervical spine injuries affect from 1.9% to 4.6% of subjects reporting a blunt trauma, and up to 5.9% of multiple-injured patients.

Most of spinal cord injuries are a consequence of unstable fractures of the cervical spine.

An accurate and early diagnosis is mandatory to prevent neurological damage in unstable fractures.

Classic and newer classifications are primarily based on features identifiable by using conventional imaging and CT scan, which are the most available modalities at most trauma centers.

Even though multidetector-CT remains superior in assessing with high accuracy bone injuries, MRI is the most sensitive modality for detecting soft tissues injuries and spinal cord damage.

1. Introduction

Spinal traumas represent a significant proportion of muscle-skeletal injuries worldwide.

Acute cervical spine injuries affect from 1.9% to 4.6% of subjects reporting a blunt trauma, and up to 5.9% of multiple-injured patients [1].

Most of spinal cord injuries (SCI) are a consequence of unstable fractures of the cervical spine.

SCI are an important cause of disability among young adults and working subjects, with high burden for both the individuals and society.

Spinal traumas involve a complex structure with components having different traumatic susceptibility and healing capabilities.

The wide variety of lesions hampers the creation and comparison of homogeneous groups with difficulty in classifying spinal fractures, in evaluating instability, and in the assessing the indication and efficacy of different treatments.

Despite of the numerous classifications of spinal injuries proposed for guide therapeutic strategies and for predict outcome, to date there are not universally accepted algorithms as to need and timing of surgery and on the most appropriate intervention techniques. However, an accurate and early diagnosis is mandatory to prevent neurological damage in unstable fractures.

Classic and newer classifications are primarily based on features identifiable by using conventional imaging and CT scan, which are the most available modalities at most trauma centers. However, MRI can aid in the diagnosis of subtle injuries to the disc-ligamentous complex (DLC).

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Even though multidetector-CT (MDCT) remains superior in assessing with high accuracy bone injuries, MRI is the most sensitive modality for detecting soft tissues injuries and is the only modality for evaluating spinal cord damage. MRI is the method of choice in examining patients with SCI. Quantitative and qualitative parameters measured on MRI have a significant role in predicting initial severity of neurological status and outcome.

The injury patterns differ for the UCS and LCS. The combination of upper and lower cervical spine injuries in a single patient is inusual.

Missed, incorrect or delayed diagnosis all impact negatively on outcome.

Acute cervical spine injuries affect from 1.9% to 4.6% of subjects reporting a blunt trauma, and up to 5.9% of multiple-injured patients [1].

Cervical spine injuries (CSIs) concentrate at the extremities of the segment, with about one third involving C2 and one half C6 or C7.

In US, CSIs occur in 150.000 people per year, 11.000 of which report spinal cord damage, with an estimated 20% of all death for traffic accidents being due to a severe spinal cord injuries [2].

CSI victims mainly are young men (aged 16–30; M:F 4:1) owing to high-energy traumas, such as traffic accidents, fall, assaults, and sport activities, in descending order. Only 1–3% of fatal spinal cord injuries occur in people before 15 years. Most of studies report a second peak of incidence in adults over 65 years of age.

Injuries in older people usully result from low-energy trauma, such as falling from standing or even seated height because of osteoporosis and stiffening in ageing spine.

As many as one-third of polytrauma patients have a closed head injury that increases the risk of cervical spine injury by 8.5% [3].

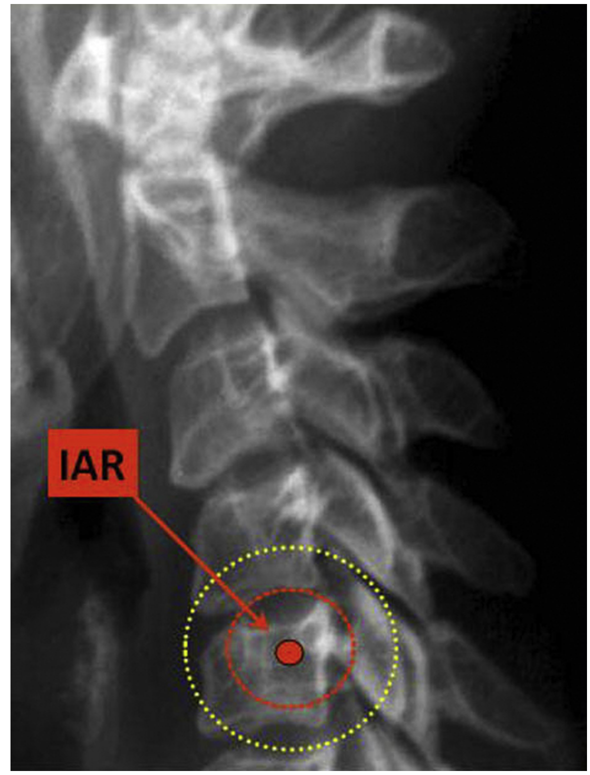

Fig. 1. Lateral radiograph of the cervical spine in flexion. During flexion–extension the vertebra moves around a transverse rotation axis placed in the subjacent vertebral body. Both the endplates and the facet joints perform two circumference arcs around the same rotation centre.

2. Biomechanics of the cervical spine

The UCS segment (C0-C1-C2) and subaxial cervical spine (SCS) (C3 -C7) have distinct anatomic features and functional programs.

The middle and lower cervical spine segments have similar anatomic and functional characteristics. Inside the subaxial cervical spine every motion segment (MS) formed by two adjacent vertebrae along with disc and ligaments, exhibits the same biomechanical characteristics as the whole spine.

Each MS has six degrees of freedom (three rotations around and three translations along) in relation to each of the three axes of the space.

The primary motion at the lower cervical spine is flexion-extension in the sagittal plane around an average instantaneous axis of rotation (IAR) for each MS located inside the posterior half of the body of the inferior vertebra. The low position of the rotation centers accounts for a coupled movement of antelisthesis maximal at C2-C3 (2–3 mm) (Fig. 1) [4].

Rotation and lateral bending are coupled motions in the lower cervical spine because of the inclination of the facet joints.

The ligaments provide passive stability and check movements. Spinal ligaments are pretensioned for prevent spinal cord compression by bulking during motion and posture, with flava ligaments (FLs) having the highest preload and the highest percentage of elastic fibres inside [5]. FLs are the main restrainers of flexion inside the posterior ligamentous complex (PLC). PLC also includes the supraspinous ligament, interspinous ligament, and articular facet capsules. PLC alternates to posterior bony complexes and serves as posterior tension band of the spinal column to control flexion, translation, distraction, axial rotation.

Facet joints are inclined approximately 45° from the horizontal plane and opposite translational, rotational, and torsional forces.

Compression loads in the lower cervical spine are resisted by the intervertebral disc, vertebral body, and, depending on the position of the spine, the facet joints.

The normal function of the spine presupposes its stability. Stability is the ability of the spine to prevent neurological damage and progressive deformity or pain under physiological loads and within a normal range of motion (ROM) [6], and is based upon the integrity of both bony and capsular-ligamentous components.

The definition of spine stability is an ongoing research field. Even though spinal injuries are distinctly divided in stable and unstable, all spinal components contribute to stability so that any injury of whatever spinal structure creates a some degree of instability which is not an all or nothing phenomenon. In fact, the complete instability is rare.

The key for the proper functioning and stability of the spine is the highly non-linear load/motion relationship. At smaller loads and at the beginning of motion, near to neutral posture (neutral zone NZ), the MSs oppose scarce resistance and the spine deforms easily. Under larger loads and towards the end of ROM, the resistance of the spine quickly increases (elastic zone EZ) because of mounting tension of ligaments and joint capsules wich allow for relatively less displacement (Fig. 2) [7].

The biphasic nonlinear behaviour of the spinal joints meets two opposed needs: to facilitate motion near the neutral posture with a little muscle effort and to ensure stability at the end of joint excursion. Stability implies an appropriate relationship between the NZ and EZ and an abnormal increase of NZ often occurs in case of instability, regardless of any increase of ROM.

Biomechanics of the spine may be completely subverted in subjects with a rigid spine, either old people with advanced degenerative spine (DS), or patients suffering from ankylosing spondylitis (AS) or diffuse idiopathic skeletal hyperostosis (DISH) [8]. In ankylosing spines low-energy traumas produce effects similar to those generated by high-energy traumas in normal spines.

In a DS, disc collapse and disruption shifts the weight loads onto the facet joints (up to 70%), with relative stress-shielding of the anterior

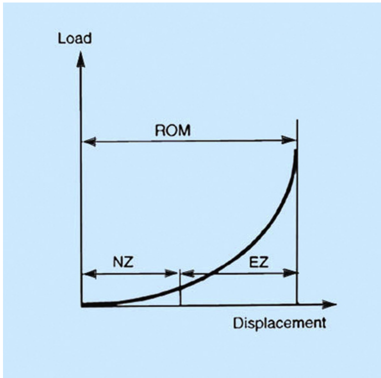

Fig. 2. Load/displacement curve. The load/displacement curve of the spine is not linear. The range of motion of the spinal joints includes an initial neutral zone (NZ) with relatively large displacements at low loads followed by an elastic zone (EZ) that requires more load per unit of displacement because of the increasing tension of capsules and ligaments.

bodies, responsible of local bone loss and weakening (Wolff's law) favouring anterior vertebral body failure. Any bone loss induces ad exponential strenght loss [9].

In AS and DISH, interbody vertebral fusion removes the shock-absorber function of spinal discs, overloading the vertebral bodies weakened in AS by the osteoporosis. In addition, with fusion of MSs, it creates an unique bloc which under traumatic displacements generates long lever arms favouring stress concentration and mechanical failure, often with a horizontal orientation just like a long bone. A rigid spine also ill dissipates forces and transmits them to adjacent mobile MSs with junctional pathology.

3. Classification of SCS traumas: a work in progress

The subaxial cervical spine is involved in 65% of cervical fractures and accounts for the majority of spinal cord injuries, but despite the high incidence the classification and management of these lesions remain controversial.

Spinal traumas involve a complex structure with components having different injury susceptibility and healing potentiality.

At moment of injury, the interaction of numerous variables creates a great variety of lesions which hamper the creation and comparison of homogeneous groups, with difficulties in classifying spinal lesions, in assessing an eventual instability, and in defining the indication and outcome of different treatment strategies.

The management of SCS depends on a number of variables, including neurologic injury, fracture pattern and severity, vertebral alignment, presence and degree of instability.

A clinically relevant classification system should consider all the variables, stratify lesions according their severity, provide prognostic information, and guide clinical decision-making.

Finally, to be useful in the clinical practice, a classification must also be easy to apply and create a common language between specialists having a good reproducibility.

Even though in injuries involving the cervical spine any inaccuracy could lead to severe outcomes, a gold standard classification system is not actually available and the lack of a consistent and precise terminology continues to hamper communication between specialists.

Various classification schemes have been proposed over time each one representing an evolution of previous ones.

In 1970, Holdsworth [10] was the first to conceive a comprehensive classification of spinal traumas, also including the cervical spine. It was a mechanistic system based on a concept of spinal stability ensured by the integrity and functional interplay of two vertical columns. The anterior column is formed by the disco-vertebral joints and anterior and

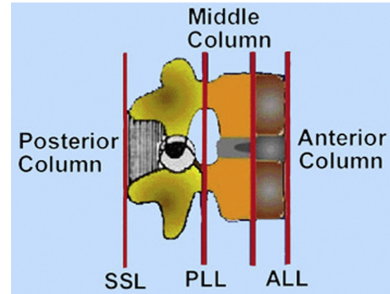

Fig. 3. Three-column concept of spinal stability by Denis. Spinal stability depends on the integrity of three vertical columns. This model divides the Holdsworth's anterior column in an anterior and middle columns giving a pivotal role to the middle column and the PLL. Abbreviations: SSL = supraspinous ligament; PLL = posterior longitudinal ligament; ALL = anterior longitudinal ligament.

posterior longitudinal ligaments (ALL and PLL) working in compression, while the posterior column includes the posterior arcs joined by the posterior ligament complex (PLC) and works like a tension band. Holdswort's model was the first to differentiate stable and unstable fracture and to recognize the role of PLC in ensuring spinal stability, a concept revealed crucial in the management of all spinal traumas.

In 1983, Denis proposed a different spinal stability model based on the function and integrity of three vertical longitudinal columns. Denis divided the spine in an anterior column comprising of anterior halves of discs and vertebral bodies joined by the ALL, in a middle column, formed by posterior vertebral bodies and discs joined by the PLL, and in a posterior column formed by the bones, ligaments and joint capsules of the neural arcs (Fig. 3) [11].

According to Denis, the PLC failure alone is not sufficient to generate spinal instability and only the contemporary failure of two out of three spinal columns can generate instability. In Denis's scheme emphasis is given to the status of middle column status and its ligament, the PLL. Althoug was conceived for classifying thoraco-lumbar traumas, Denis model has gained wide acceptance also in the assessment of cervical spine stability [11].

After Holdsworth, two classifications systems specific for the CSI were proposed. In 1982, Allen and Ferguson (A–F) proposed another mechanistic classification system based on conventional radiology, including: compressive flexion, distractive flexion, compressive extension, distractive extension, vertical compression, and lateral flexion. These six more common major categories of traumas (phylogenies), was further divided in stages according to damage severity [12]. The assumption was that the same conditions of spinal posture, direction and magnitude of vector forces generate reproducible patterns of traumas.

In 1986, Harris [13] modified the scheme proposed by Allen replacing distractive with rotation type injuries, in both flexion and extension.

However, the mechanism of injury not always can be inferred from post-injury radiographs as a wide range of fracture patterns can result from the same force vectors because of spinal buckling. All mechanistic systems being speculative and arbitrary, fail the requirements of reliability and clinical relevance, neither consider enough the energy underlying different traumas [14,15].

Subsequent classifications preferred to quantify injuries as a continuum through severity scales objectively composed. In 2007, Vaccaro and the Spinal Trauma Study Group (STSG) proposed The Sub-axial Injury Classification (SLIC) and Severity Scale, a new scheme which abandons the inferred biomechanics of injuries based on the final spine position of previous classifications to describe lesions morphology, and is based on a combination of imaging and clinical evaluations [14]. SLIC classification starts from the morphological damage which describes the structural damage and relationship of vertebrae, on which it depends the mechanical stability. The most severe damage determines

Table 1
SLIC Scale [14].

	Points
Morphology	
No abnormality	0
Compression	1
Burst	+1- = 2
Distraction (*e.g.*, facet perch, hyperextension)	3
Rotation/translation (*e.g.*, facet dislocation, unstable teardrop or advanced staged flexion compression injury)	4
Disco-ligamentous complex (DLC)	
Intact	0
Indeterminate (*e.g.*, isolated widening, MRI signal change only)	1
Disrupted (*e.g.*, widening of disc space, facet perch or dislocation)	2
Neurological status	
Intact	0
Root injury	1
Complete cord injury	2
Incomplete cord injury	3
Continuous cord compression in setting of neuro deficit (Neuro Modifier)	+1

the score.

The SLIC scheme is the first to introduce MDCT imaging in evaluation and grading of morphological damage and to address also the disc-ligamentous complex (DLC) damage and neurologic status it consider along with the damage morphology as major and independent determinants of prognosis and management (Table 1). Main groups and subgroups of injuries are both stratified and numerically scored according increasing degrees of severity, in order to guide clinical decision making (Table 1). Injury morphology distinguishes compression injuries, distraction injuries, resulting in vertical dissociation of MSs, and the most severe rotation-translation traumas caused from horizontal, shearing vector forces. The damage of DLC is proportional to instability degree and always occurs for distractive or translational forces. The assessment of DLC is a weakness of SLIC system because its status remains undetermined on many occasions when MRI imaging shows isolated abnormal findings whose clinical relevance remains uncertain. The degree of neurologic deficit reflects the severity of injury and is the single most important influencer of therapy. Clinical and imaging findings combined form a numeric score. High scores (≥ 5) indicate surgical intervention, low scores (≤ 3) conservative management, while for injuries with intermediate score (4) the treatment (conservative vs surgical) depends on the individual preferences of the specialists and eventual patient comobidities. In an early internal validation, injury morphology demonstrated moderate (Fleiss kappa agreement coefficient) interrater agreement (0,51), DLC showed fair (k 0.33) interrater agreement, while neurologic status proved to be most reliable (k 0.62) [16]. Agreement between raters about the SLIC score algorithm was obtained in 91.8% of cases. SLIC reliability compared favorably to the Allen & Ferguson (A–F) and Harris systems.

However, a subsequent external validation study of SLIC scheme by 12 surgeons on 51 randomly selected consecutive cases, reported only poor (0,29) and moderate (0,46) kappa agreement coefficients for morphology and DLC status, respectively [17].

In a more recent multinational study on 34 random patients with SCS injuries involving 13 spine surgeons of the Spine Trauma Study Group asked to classify patients using A–F and SLIC systems, A–F mechanistic types showed better inter-observer reliability than the SLIC morphological types. Among the SLIC variables, once again the DLC status and the total SLIC had the least agreement.

Given the limits of SLIC classification, the AOSpine Classification Group and the Spine Knowledge Forum in 2008 revised the comprehensive but complex AO-Magerl classification [18] proposing a slender scheme including the classical three patterns of injury deemed to be relevant for the prognosis: compression injuries (type A), posterior or anterior distraction (type B), and dislocation-translation, (type C), each one containing subgroups [19].

AO scheme also includes four additional case-specific modifiers (M1-M4) which describe particular conditions also relevant to clinical decision making. M1 describes a posterior capsulo-ligamentous complex injury. M2 describes a traumatic disc herniation. M3 describes spinal stiffening: DISH, AS, OPLL, OLF, conditions that may either indicate or exclude surgery.

Unique to this classification is the assessment of the facets added as a separate descriptor. Facet injuries can present alone or with an A,B, or C morphological type. M4 describes signs of vertebral artery injury [19].

The new AO classification system deserves special attention to facet joints status. Facet injuries are graded starting from little nondisplaced single facet fractures (F1: fragment < 1 cm or < 40% lateral mass), to larger potentially unstable fractures (F2: > 1 cm or > 40% of lateral mass), up to floating lateral masses (F3) and subluxated, perched, dislocated facets (F4) [19].

Morphology of the fracture and neurological status, are graded and used to guide treatment, along with eventual clinical case-specific modifiers [19]. Like for the SLIC scheme, neurological status is graded through six subtypes ranging from neurologically intact (N0), to N1 (transient neurologic deficit that has completely resolved by the time of clinical examination), N2 (radiculopathy), up to incomplete (N3) and complete spinal cord injuries (N4). A NX subtype describes a neurologically indeterminate status.

At an initial assessment by the authors, overall interobserver and intraobserver reliabilities of AO system were good (k 0,64 and k 0,75). Consistent with these results was a study by Urrutia et al. who also reported substantial interobserver agreement for all main categories (k range 0,57–0,64), and moderate agreement for subtypes (0,54–0,60) [20]. However, in a study by Silva et al who tested the reliability and validity of AO system employing 5 blinded researchers on 51 subjects at two different times, only mild (Type A0) and most severe (Type C) injuries had a high rate of interobserver agreement (k 0,67 and 0,68). Facet modifiers and intermediate injury patterns did not [21].

Further studies will serve to define the reliability of newer classification in comparison to classic schemes.

4. The morphological damage

The morphological damage refers to the structural integrity and relationships of vertebrae after a blunt trauma on which immediate mechanical instability depends.

There are four main mechanism of spinal injury, including compression, hyperflexion with posterior distraction, hyperextension with anterior distraction, and dislocation/rotation.

Each of main injury mechanisms has an own recognizable or inferable radiologic pattern or "footprint" [22]. However, to the main mechanism it may often associate other vector forces creating more complex traumas more difficult to recognize by imaging.

In compression and burst fractures (Fig. 4), there is a vertebral body height loss with no signs of translation or distraction. A teardrop fragment morphology also can occur by compression alone with no distraction. Simple compression receives 1 point and burst fractures 2 points in the SLIC scheme [14].

Undisplaced or minimally displaced lateral mass, facet, laminar, or spinous process fractures, without distraction, are also classified as compression injuries and may occur in isolation or with vertebral body compression or burst [14].

A distraction injury consists in anatomical dissociation of the MSs along the vertical axis of the spine wich can occur anteriorly, by hyperextension, or posteriorly, after hyperflexion. In both cases, for these injuries to occur, large forces have to overcome the strength of the ALL and anterior annulus (with or without PLL), and the facet capsules and PLC, respectively. These injuries therefore tend to be more severe and unstable.

Fig. 4. (a and b) A 39-year-old-man victim of diving trauma. Sagittal midline FSE T2-weighted (a) and GRE T2*-weighted (b) MR images. Typical pure compressive trauma to head vertex causing burst fracture of C3 vertebral body and compression fractures of superior endplates of C7 to D2 vertebral bodies. Spinal cord edema with spindle-shaped enlargement spanning from C2 to C4 containing central hypointense spots of hemorrhage at epicenter of trauma visible only with the more sensitive GRE sequence.

Fig. 5. (a and b) A 35-year-old man victim of lateral car collision. Parasagittal reformatted CT scans through the right C4-C5 interfacetal joints (a), midsagittal (b) reformatted CT image. A flexion and rotation injury with unilateral facet dislocation of C4 right inferior articular process lying in front of the C5 superior process. The vertebral dislocation occurs on the side opposite the direction of rotation, where posterior ligaments and disc anulus are torn. Vertebral body translation remains inferior to 50% of AP diameter of endplate below. Fractures of the articular facets and pillars most often occur, generally with a vertical orientation, like in this case. Unilateral facet dislocation may cause radiculopathy, cord injury or isolated neck pain.

The flexion-distraction injuries include unilateral facet dislocations (by hyperflexion plus rotation) (Fig. 5) bilateral facet dislocations (Fig. 6), flexion teardrop fractures (Fig. 7), Chance-type fractures, and hyperflexion sprains (purely ligamentous damage). Hyperflexion-distraction injuries show ventral disc space narrowing along with posterior disc and posterior elements widening and kyphotic deformity [23].

Facets can be subluxated or perched. Subluxation consists in less than 50% overlap of the articular surfaces or more than 2 mm of diastasis [14]. Some anterior translation of the vertebral body and neural arc may occur. Among all cervical spine injuries, the flexion teardrop fracture represents one of the most severe and unstable fractures. It not only causes the disruption of the posterior ligaments, like other hyperflexion injuries, but also of the anterior soft constraints at level of trauma. A triangular detachement of anteroinferior vertebral body corner, generally higher than wide, (teardrop) or quadrangular, of entire ventral vertebral body, result from impaction of rotating ventral vertebral body against subjacent endplate. In the classic most severe form a three-part biplane fracture also includes a sagittal vertebral body fracture extended to neural arc. The latter pattern is almost always associated with permanent neurologic deficit due to the severe narrowing of the spinal canal by retropulsed fragments and hyperkyphotic angulation (Fig. 7).

The extension-distraction injuries lead to disruption of anterior disc and ALL and occur in motor vehicle accidents or in elderly for falls from standing (Fig. 8). The anterior disc space is enlarged, with or without posterior column fracture and vertebral body can be displaced posteriorly or anteriorly, in the last case with preservation of spinolaminar line because of associated posterior column fractures [23]. Extension teardrop fractures prevail in C2 and involve the anterior inferior

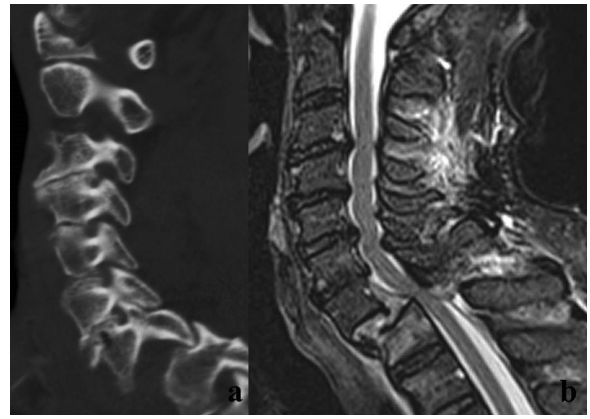

Fig. 6. (a and b) A 61-year-old-man, victim of high energy with neck hyperflexion. Parasagittal right reformatted CT image (a), sagittal midline STIR-weighted MR image (b). Bilateral dislocation “over the top” of the inferior C6 facets (a) on C7 superior facets, with vertebral displacement of about 50% of AP diameter of the subjacent vertebral body, deformed by compression (b). This is a borderline situation for cutoff value between flexion-distraction and translation-rotation injuries. Notice the disruption of all posterior ligaments, including the joint capsules and the neck muscles edema, as well as the disc and ALL disruption, marked from a satellite prevertebral hematoma. Stripping and elevation of PLL with enlargement of anterior epidural space containing some disc material. The displaced disc however does not protrude beyond the posterior cortex of the vertebral body below, nor compress the spinal cord. For some Authors this does not constitute a traumatic disc herniation [65]. The spinal cord is rather compressed between the C6 neural arc and C7 vertebral body posterior edge.

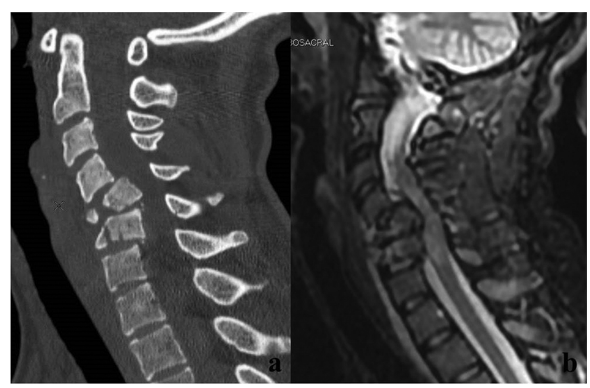

Fig. 7. (a and b) A 22-year-old-woman victim of car accident with hyperflexion and compression trauma. Sagittal midline reformatted CT (a) and axial (b) TC images, sagittal midline FSE T2-weighted MR image (c). A double teardrop fracture involving C5 and C6 vertebral bodies. At C5 the detached fragment involves the entire vertebral body height with a quadrangular morphology, while a C6 it does not reach the superior endplate and has the classical triangular shape. Both posterior vertebral bodies are displaced posteriorly and rotated. Compression of spinal cord showing multilevel edema and enlargement with little hypointense spots of hemorrhage inside.

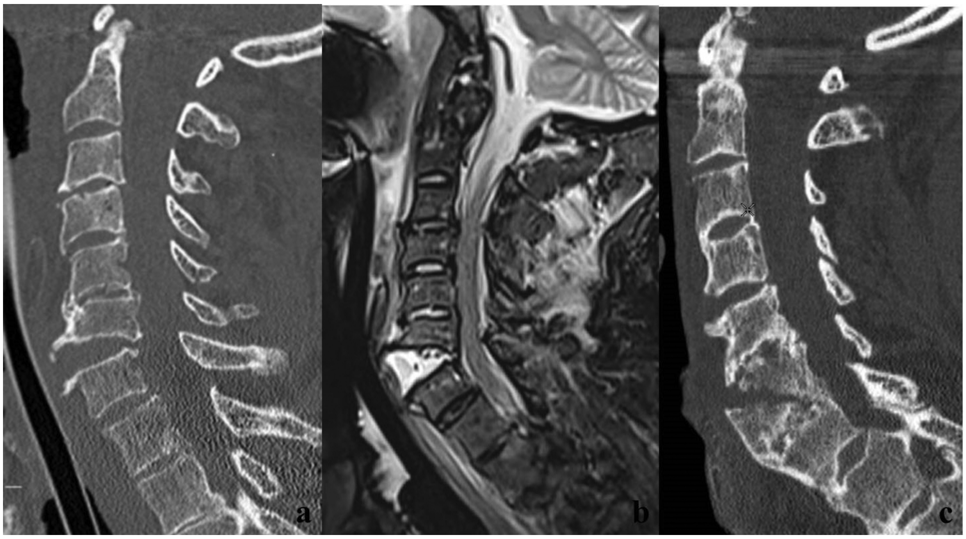

Fig. 8. (a-c) A 72-year-old man slipped in the bathroom with facial trauma and neck hyperextension (a and b). Midline reformatted CT image (a) showing a marked enlargement of C6-C7 anterior intervertebral disc, along with posterior displacement of C6. A disc angle greater than 18° on CT is concerning for anterior cervical disco-ligamentous injury and indicates a MRI evaluation. On MR, the disc injury appears as asymmetric widening of an isolated disc space along with focal signal changes, often extended to contiguous other damaged soft tissues. Axial CT sequence (not shown) excluded impaction fractures involving posterior arc elements. Hyperextension fractures prevail in the rigid spines. A 53 year-old-man with AS after a fall from standing (c). Sagittal midline reformatted CT image showing a horizontal fracture starting from the vertebral body and extended to posterior fused facet joints.

vertebral body edge with a fragment appearing tipically wider than high. This morphology is related to traction effects exerted by anterior annulus fibers. Compression fractures of neural arc and facial trauma often coexist [24]. In the SLIC scheme, distractive injuries receive 3 point as type of morphological damage and additional 2 points for the ligamentous damage which togheter suggest surgery [14]. Generally, the extension-distraction spinal injuries are considered more severe than posterior distraction ones in that the stronger anterior spinal restraints require relatively higher energy before failure. In the AO-Spine classification these injuries are classified as B3 traumas [19].

Translation/rotation injuries are provoked by shearing forces acting perpendicular to spinal axis through an unilateral or bilateral facets dislocation or fracture-dislocation, but often imply a contemporary posterior distraction, with facet loking. An offset over 3,5 mm and over 50% of subjacent vertebral body represents the cutoff value for this injury with bilateral facets locking resulting in a vertebral body anterior subluxation pair to or over 50% (Fig. 9). In every case there is an offset in the spinolaminar line, but in children a step within 2 mm in C2 can normally occur [24].

Injury morphology can be cleared by conventional plain radiographs, CT, or MRI.

4.1. Selection of patients to imaging-clearance of the cervical spine

Soon after airway protection, cervical spine immobilization is the next step of the Advanced Trauma Life Support protocol. In any blunt trauma patient the cervical spine has to be considered injuried until proved otherwise and, in order to safely remove spinal precautions, it must to be before “cleared”. Cervical spine clearance consists in the confident and ultimate exclusion of a cervical spine injury by clinic and/or imaging.

Subjects recognized as at risk for cervical spine injury and selected for imaging represent a very heterogeneous group for whom different imaging modalities can be appropriate in different cases. Screening protocols vary between different trauma centers also depending on the available resources and technical capabilities.

The traditional initial study of the acutely injured cervical spine has been with the three-view radiography series (anteroposterior, lateral, and open-mouth), with eventual addition of swimmer’s or oblique views. The continued value of plain imaging is due to its wide availability, low cost, and the widespread experience in their interpretation [25].

Cervical spine plain imaging is one of most common exams performed on trauma patients throughout all the developed countries, but its yield is very low, with just 0.9%–5% of studies showing fractures

Fig. 9. (a–c) Young rider victim of a high speed collision (a,b). Sagittal midline reformatted CT (a) and STIR-weighted MR scan (b). Complete dislocation of C5 on C6 with uncovering of the disc on which some parts of the inferior C5 cortical endplate remain. Endplates are an integral part of the intervertebral disc and sometimes remain adherent to it. Severe compression of the spinal cord between the posterior arc of subluxated vertebra and the posterosuperior corner of subjacent vertebral body. An offset over 3,5 mm and over 50% of subjacent vertebral body represents the cutoff value for this injury. Disruption of all anterior and posterior ligaments with high instability. Diffuse edema of neck muscles. These can also occur in ankylosed spines by low energy traumas like a fall from standing. Midline reformatted CT scan in a 50-year-old man with AS (c). Notice the diffuse fusion of anterior and posterior spine, with calcification also of tectorial membrane and alar ligaments.

Table 2
NEXUS criteria for not imaging [27].

Imaging not necessary in patients meeting all of 5 following criteria:
1 No midline cervical spine tenderness
2 No focal neurological deficit
3 Normal level of alertness
4 No intoxication
5 No painful distraction injury

Table 3
Canadian C-spine rule [29].

Imaging not necessary if patients are alert GCS 15) and all of the conditions below are met.
1 No high-risk factor present:
Age 65 or more years
Dangerous mechanism, including:
fall from > 3 m/5 stairs
axial load to head (diving)
high-speed vehicular crash
bicycle crash
Paresthesias in extremities
2. Any low-risk factor present, including:
Simple rear-end vehicular crash mechanism, excluding:
pushed into oncoming traffic
hit by bus/large truck
Rollover
hit by high-speed vehicle
Sitting position in emergency department
Ambulatory at any time
Delayed onset of neck pain
Absence of midline cervical tenderness
3. Able to actively rotate neck (45 degrees left and right)

[26–28]. Although in itself not expensive, standard imaging becomes a costs problem for its large use, but in time of increasing attention for healt care expenditure, resources optimization is need. Two large prospective multicenter observational trials have tried to define optimal clinical criteria to select subjects appropriately for imaging. The National Emergency X-Ray Utilization Study (NEXUS) provided a validation of five clinical criteria simple to apply in the daily practice (Table 2), based on 34.069 trauma subjects examined in 21 emergency departments with a wide range of sizes and facilities types. NEXUS rules application in 818 patients having cervical fractures missed only 8 cases, with only 2 being clinically significant. Hence, the rules for not imaging showed high sensitivity (99,6%) in correctly identified subjects at risk of fracture, but with a specificity of just 12,6% the capacity of avoiding unnecessary imaging was limited [27]. In 2001, the Canadian Cervical Spine study group selected prospectively own new parameters, through two phases of validation from cohorts of 8924 and 8283 patients respectively, examined across ten hospitals (Table 3). CC-spine rules afforded 100% of sensitivity and 45,1% of specificity for injuries, reaching a superior efficacy in avoiding unnecessary imaging [29]. The higher specificity was the main strength of CC-Spine Rule, but with the flaw of a greater complexity. Despite a long debate between the two research groups, no clear advantage of one prediction rule over the another has been demonstrated. Both rules sets have proved to be powerful predictors of cervical spine injury and in line with them, a metanalysis by Anderson et al, concluded that low-risk alert subjects, able to perform a complete range of active motion, did not need collar nor imaging. According to the Authors, in these patients an accurate clinical evaluation consented a safe clearance of the spine with a sensitivity of 98.1% and a negative predictive value of 99.8% [28].

The American College of Radiology has accepted both the NEXUS and CC-spine criteria in its appropriateness guidelines for screening patients before imaging the cervical spine [29].

Since the definition of Nexus and C-Spine low-risk criteria, the clearance of the cervical spine based on the clinical evaluation alone has become the standard procedure in emergency setting for adult alert subjects with no midline posterior tenderness, neurologic symptoms, or distracting injuries.

In elderly patients over 65, different biomechanical conditions due to osteoporosis and degenerative changes favour low-energy spinal traumas. Moreover, in patients with anchylosing spinal pathologies, very low-energy traumas may create lesions as severe as that provoked by high-energy mechanisms in normal spines. In both degenerative and anchylosing-rigid spines clinical prediction rules are harder to apply. For these subjects a very lower threshold for imaging use is mandatory.

4.2. Role of plain radiographs and CT

The main problem of standard imaging remains the well demonstrated limited sensitivity (30–60%) in bony and ligamentous injuries detection, mainly in multitrauma subjects in whom the incidence of injury is highest. In patients uncooperative, with major trauma and with head or immobilizing injuries, plain imaging is both technically inadequate and time consuming. In a prospective study on high risk patients, Diaz et al reported for radiography a 52.3% of missed fractures rate, with 17.5% of unstable fractures [30]. Concordingly, also a metanalysis by Holmes et al by comparing standard with CT imaging obtained a global sensitivity of 52% and 98% respectively [31].

As missed injury can have devastating consequences and costs largely overcoming that of a large number of unnecessary imaging studies, over the last years the imaging of acute trauma patients has progressively changed, shifting from standard radiographs versus CT. Duane et al compared prospectively the reliability of the clinical examination with that of CT in 534 blunt traumas, reporting 7 false negative cases at clinical examination of subjects awake and alert, without distracting injuries. The study concluded that clinical examination cannot be relied upon to rule out cervical spine fractures [32].

At first, CT was used as complementary and problem-solving modality for assessing limited spinal segments. Initial multidetector-CT (MDCT) machines began to explore the entire cervical spine, but the poor quality of reformatted images did still leave a certain role to standard imaging. Nevertheless, during the early 1990s, Nunez et al in a prospective series of 800 multisystem trauma patients, already reported a more than double sensitivity for CT (98,5%), in comparison to radiographies (43%) [33]. Actual MDCT imaging has obtained increasing acceptance as first choice modality thanks to wide availability, quick accessibility, and excellent image quality, with 99% of sensitivity of 100% of specificity for CSIs [34]. When MDCT is used as first imaging approach, it gains precious time within the golden hour accelerating the clinical management.

MDCT offers major advantages for the assessment of occipito-cervical and cervicothoracic junctions injuries which alone account for 17% of CSIs. MDCT also consents a precise evaluation of posterior spine injuries it depicts with a superb detail though reformatted 2D and 3D high resolution images, starting from isotropic submillimeter axial data sets. Three-dimensional volume rendering recontructions are particularly useful in the assessment of rotatory traumas.

The accurate detection of every fracture is important because some fractures that would be classified as stable can still harbor elements that may create instability when not correctely treated. Inside the posterior spine, facet injuries are typically the result of a flexion and distraction or dislocation-rotation mechanism. Unilateral cervical spine facet fractures are the single most frequently missed significant cervical spine injury. In a study by Spector et al, patients with unilateral cervical facet fractures involving 40% of the absolute height of the intact lateral mass or with an absolute height of 1 cm, created instability and were thought at increased risk for failure of nonoperative treatment [35]. These conclusion are in line with AO Spine classification system grading facet fractures [19].

Despite the numerous advantages offered by CT, its use among the heterogeneous group of trauma patients remains controversial.

Blackmore at al. proposed guidelines for an appropriate use of CT,

Table 4
Harborview High Risk Cervical Spine Criteria [37].

1. High-energy injury mechanism
High-speed motor vehicle or motorcycle crash
Fall from height > 10 feet
2. High-risk clinical parameter
Significant head injury, including intracranial hemmorhage or persistent unconsciousness in emergency department
Neurological signs or symptoms referable to the cervical spine
Pelvic or multiple extremity fractures

using a combination of clinical prediction rules and a cost-effectiveness analysis [36]. By gathering the probability that a spinal lesion is present, the costs of the initial imaging, the costs of any adjuntive imaging test induced by false-positive or inconclusive studies, and those due to a poor outcome, CT resulted to be the most effective modality for the initial clearance of cervical spine in patients with high (over 10%) and moderate (4–10%) risk of fracture, but not for low risk people. CT effectiveness is in part due to the high frequency of inadequate plain studies needing additional tests, in part to inherent higher sensitivity consenting fewer missed injuries and better outcomes [36]. Criteria for the definition of "high risk subject" has been retrospectively developed and prospectively validated in one study by Hanson et al [37] (Table 4).

High-risk subjects for whom a CT is the primary modality to use, are patients with a rigid spine: DS, AS, DISH, ossification of PLL (OPLL), ossification of ligamenta flava (OLF), and surgically fused spine. Plain radiographs often miss the fractures which prevail in the cervicothoracic junction and, even when detect a lesion, the severity of damage is often largely underestimated. CT shows the site of fractures which are more often horizontal and prevail in the calcified discs in the AS and through midvertebral body in the DISH, the weak links created from the two diseases, respectively. Detecting precisely the extension of fractures is also important in that in the absence of a neurologic compromise, nondisplaced fractures sparing the posterior elements can be managed conservatively. The extension of fractures to posterior elemnts in less frequent in DISH in comparison to AS for the lack of facet ankylosis and PLC calcification. A whole-spine CT must always be performed owing to the high frequency of multiple noncontiguous injuries [8]. In patients sufffering AS, in particular, the risk of spinal fractures is seven times greater in comparison to normal subjects and increases with the length and duration of ankylosis. For the rigid spines, a low threshold also for using MRI is recommended, in front of the high frequency of epidural hematomas, unstable injuries and spinal cord damage [8].

Some literature advocates the extension of CT also to low-risk trauma subjects in front of the limits of conventional imaging and the large supremacy of CT. The current American College of Radiology recommendation is for using MDCT in patients with distracting traumas but some Authors declare an overall sensitivity of 99% of clinical examination alone, even in the presence of distracting injuries [38].

The overuse of MDCT also favoured from the availability of machines not only increases the healt care costs, but also raises concerns of radiation exposure. The actual estimated expenditure in the United States for imaging the cervical spine is 3,4 billion of dollars, while the dose absorbed by the thyroid when a 16–detector row CT is used can reach 75.6 mGy. Employing technical programs to lower radiation doses in CT studies, performing a careful selection of patient for imaging, and using radiographs in low-risk subjects are the main actual options for limit inappropriate exposure and cost [23].

4.3. CT angiography

MDCT imaging after contrast medium administration consents the assessment of neck vessels injuries. In numerous trauma centers MDCT angiography is the screening modality of choice for subjects with suspect vascular injury, preferred to conventional angiography for its celerity, accuracy and non invasiveness

Up to 1% of nonpenetrating neck traumas are complicated by blunt cerebrovascular injuries (BCVIs). Patients can present with symptoms despite an inconclusive initial routine diagnostic workup, but often become symptomatic even 72 h after trauma, which is in up to 80% of cases due to a motor vehicle crash. Screening of these traumas through an accurate clinical and imaging evaluation and an early anticoagulation and antiplatelet therapy, can prevent deficit and improve outcome.

Radiologically, fractures of CCJ, foramen trasversarium, vertebral dislocations, severe hyperextension or hyperflexion cervical injuries, are indications for a screening by MDCT angiography which has replaced over time DSA angiography thanks to its widespread availability and for being easily inserted in a whole-body CT study [39].

Vertebral arteries are mainly injured in the V2 segment for extrinsic compression, or trombosis, dissections or pseudoaneurysm responsible of distal embolization. Vertebral arteries injuried are a specific modifier (M4) in the actual AOSpine classification [19].

Imaging findings consist in nonstenotic luminal irregularities secondary to intimal injury, a wall thickening by intramural hematoma, intraluminal intimal flap, intraluminal thrombosis, pseudoaneurysm appearing as focal eccentric outpouchings of the arterial lumen, active noncontained extravasation, or arteriovenous shunt with anlargement and early filling of efferent vein [23,24]. On MR imaging, axial T1 images with fat-saturation or black-blood techniques are helpful to detect even subtle subintimal dissections [40,41]. Complete occlusion, representing the most frequent carotid blunt injury, is most often gradual in this vessel, whereas vertebral occlusions are usually abrupt [42,43].

According to Biffl classification, a grade 1 injury is a luminal stenosis < 25% by dissection, intraluminal thrombus or intramural hematoma; a grade 2 injury is a narrowing > 25%. A pseudoaneurysm is a grade 3 lesion, a grade 4 injury an occlusion, a grade 5 injury a vessel transection or a arteriovenous fistula. While for vertebral arteries the stroke rate is 24% regardeless of grade, for carotid arteries the rate raised from 3% up to 100% from 1 to grade 5 [44].

4.4. Role of MR imaging

With the increasing availability of MRI, many patients are being evaluated by both MDCT and MR modalities during their acute injury work-up. However, in the assessment of morphological damage, MRI is not the modality of choice for the initial evaluation of bone injuries. Even though some investigator have stated that a negative MRI should be adequate to clear the cervical spine after trauma, MRI is insensitive to some spinal fractures, expecially those involving posterior arc elements. This reduced sensivity is probably due to the complex geometry, little size, and paucity of spongy bone and medullary space inside posterior elements (Fig. 10). A study by Klein et al, using CT as the gold standard, reported a pooled sensitivity for posterior element fractures of 11,5% and for cervical anterior fractures of 36,7% [45]. Inside the vertebral bodies MR can better depict acute compressive marrow edema by axial loading, even without any associated deformity or cortical break showing a greater extension of trauma in comparison to CT (Fig. 4). However, the presence and degree of edema vary and fractures without compression or fractures with distraction do not reliably generate marrow edema and can lead to a false negative studies or miss the acuity of a fracture (Fig. 10) [46].

5. Disc-ligament complex damage

The majority of the cervical spinal cord injuries results from unstable fractures of the spine which can be initially clinically unapparent. Only one third of spinal trauma patients have neurological deficit at presentation. Patients with occult spine fractures or ligamentous lesions can become symptomatic during stay in emergency department [2].

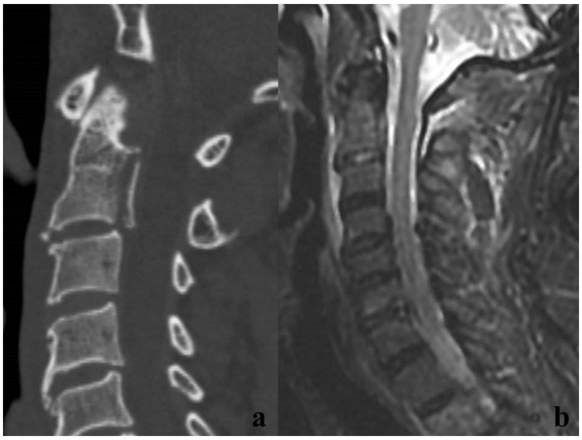

Fig. 10. (a and b) A 62-year man hit by a car. Parasagittal reformatted CT scan (a) showing a transversal vertical fracture of posterior C2 vertebral body. Sagittal STIR-weighted MR image not depicting any signal abnormality inside C2 spongy bone. The only sign of trauma is the little hemorrhagic collection in the prevertebral space.

About 89% of cervical spine post-traumatic lesions detected on postmortem imaging involve soft tissues, with or without bone lesions [47]. On clinical imaging, pure ligamentous cervical spine injuries, without fractures are rare, with a prevalence of only 0,6% which does not vary significantly between alert and unreliable patients [25,48]. The assessment of instability in a spinal injury is even more important in front of newer surgical techniques and hardwares.

5.1. Role of radiographs and CT

Abnormal bone relationships detected by plain radiographs and CT are the first signs of discoligamentous injuries [24]. Stability of the SCS may be defined by assessing the regularity of the anterior and posterior vertebral lines, the spinolaminar and spinous processes lines, as well as the parallelism of facet joints, and the uniformity and symmetry of disc, interspinous, interlaminar, and facet joint spaces. Distraction and translation-rotation injuries always imply a damage to ligaments and a change in the vertebral relationships.

As static imaging cannot completely exclude potentially unstable ligamentous injuries, active dynamic flexion-extension studies have been recommended in patients complaining focal pain and/or persistent posterior midline tenderness. A sagittal displacement or translation greater than 3.5 mm or over 20% of vertebral body AP diameter on either static or dynamic (flexion- extension) lateral radiographs, as well as more than 20° of sagittal plane rotation, all should suggest potential instability [49].

However, flexion-extension views may be inadequate in up to 95% of cases because of muscle spasm and patient guarding limiting the range of motion in acute setting and for the difficulty in assessing the cervicothoracic junction [50]. Finally, for the wide individual variation in the cervical curves during sagittal motion between normal subjects, no imaging criteria have been definitively validated to define an abnormal dynamic study.

Because of the insufficient contrast resolution on CT imaging, ligament edema or loss of continuity are indistinguishable from normal appearance, neverteless a recent article by Molière et al, has demonstrated that an abnormal density within the fat pad between occiput, the nuchal ligament, and erector muscles, by hemorrhage and edema, may be an indirect indicator of PLC injuries, with a sensitivity of 55% and a specificity of 97%, PPV 92%, NPV 81% [51].

Concerns for occult unstable spinal injuries are highest in obtunded, sedated, and unreliable patients, for which clinical rules to clear the cervical spine and avoid radiologic imaging are not applicable. In patients with a closed head trauma, the risk of CSI increases by 8,5% [3]. On the other hand, in these particular patients any unnecessary prolonged neck immobilization also exposes to potential complications and medicolegal consequences.

Across numerous studies the risk of unstable cervical spine injuries with negative MDCT resulted to be exceedingly low. Hogan investigated the capability of MDCT and the added value of MRI in showing soft tissue injury in 366 obtunded cervical trauma patients. With a negative predictive value of 98,9% (362 out 366) for ligamentous injury and 100% for unstable injury, CT was thought to be sufficient to exclude an unstable lesion, without the need for routine MRI [52]. Similarly, Harris among 367 blunt trauma patients cleared by CT found just one case of missed injury revealed by MRI, with a false-negative rate of only 0,3% [53], while Como found injuries missed by CT in 5 among 115 subjects (5,2%) [54]. In both studies, however, MR findings did not lead to changes of treatment. Subsequent retrospective studies also have confirmed the reliability of MDCT alone for identifying clinically significant injuries [55,56], as well as a prospective report by Bush specifically focused on alcohol and drug intoxicated patients [57].

5.2. Role of MR imaging

Other studies underline the limits of CT for identifying ligamentous injuries and recommend MR imaging. Among these, a review by Sliker reporting a general frequency of ligamentous injuries detected by MRI alone for blunt trauma at 22,7%, 80,8% of which requiring treatment. In the subset of obtunded patients the ligamentous injuries occurred in 19,5% and 69,2% warranted surgery [58]. Concordingly, in one subsequent retrospective study by Menaker, on a cohort of 203 unreliable subjects with negative CT and clinical results, MRI additional data indicated surgery in 2 cases and prolonged immobilization in 14 cases [59].

Because of these discordant conclusions the routine use of MRI for the clearance of the cervical spine in unreliable subjects remains controversial and numerous patients are left with spinal precautions despite of a normal CT.

Even though most of ligamentous traumas detected by MR are clinically insignificant, the status of the discs and ligaments remains a fundamental step of spinal stability assessment.

MR is the only imaging modality that directly depicts changes to the ligaments and discs resulting from a trauma, obviating the need to desume their damage from the mechanism of injury like on CT and conventional imaging.

MRI can detect subtle ligamentous injuries with high sensitivity. Ultrashort echo time (UTE) imaging is a new technique which can extract signals from ligaments that normally give little to no signal on conventional pulse sequences, further improving the detection of subtle lesions.

However, in assessing ligament injuries MRI offers only a limited specificity, with false positive studies which carry the risk of potential surgical overtreatment. The lack of a precise definition of ligament failure and a grading scheme for the injuries limits the specificity in predicting mechanical instability.

The black stipes of ALL and PLL can normally appear discontinuous or difficult to discern, expecially in degenerated spines (in up to 26% and 64% of disc levels, respectively), whereby an interruption in isolation cannot always be relied upon [60].

While a frank disruption or avulsion of a ligament with adjacent tissues edema, hemorrhage or bone lesion is generally considered a reliable primary sign of failure in acute setting, the significance of isolated signal changes inside a non crearly disrupted ligament remains unclear. Moreover, a normal signal in a ligament on MRI not always excludes its incompetence [61].

In the SLIC scheme, isolated signal abnormalities on MR are indeterminate and receive a score of 1. The assessment of ligaments represents the cause of lower accuracy of the DLC component inside the

SLIC classification. For these cases surgery uniquely based upon MR data is not recommended [14]. The AOSpine also includes a modifier (M1) for cases in which injury to the PLC remains indeterminate [19].

The ALL and PLL are involved in translation-rotation and distraction injuries damaging the anterior and/or middle spinal columns and become apparent when elevated by fluid, disc protrusions or displaced bone, or stripped in case of translation injuries.

In hyperflexion-distractive cervical traumas with bilateral facet dislocation, a retrospective review on 30 subject studied with MR by Carrino et al found the ALL disruption in 26.7%, disc herniation or disruption in 90%, PLL disruption (40%), and disruption of the PLC in 97% of cases [62].

In hyperextension-distractive SCS traumas, in which bone lesions are often subtle while ligamentous damage prevails, MRI can have an important role. A study by Song et al [63] on 81 patients found MR imaging to accurately demonstrate a sequence of progressive damage involving soft tissues. This sequence starts from the ALL injury (grade I), pursues through the disc damage (grade II), PLL rupture (grade III), flava ligaments/ interspinous ligament (grade IV) disruption, for ending with posterior neck muscles injury (grade V). Cord injury developed only in injuries equal to or greater than grade III (PLL rupture). Being the grade of soft tissue injury correlated with spinal cord damage, MR was predictive of outcome and guided decision making [63].

Subjects having a rigid spine are particularly prone to hyperstension injuries of the cervical spine [8].

A traumatic disc herniation occurs in up to 54% of CSIs and is found associated with 80% of bilateral facet dislocations, 60% of hyperextension injuries, 47% of central cord syndrome, and in all cases of anterior cord syndromes. The presence of a traumatic disc injuries on imaging can influence the timing and the type of surgical decompression and stabilization, or closed reduction [61]. An intervertebral disc angle greater than 18° on CT is concerning for anterior cervical discoligamentous injury, with or without additional ligamentous injury, and requires MRI evaluation [64]. Disc injury appears as asymmetric narrowing or widening of an isolated disc space and focal signal changes contiguous with other damaged soft tissues.

MRI is indicated for all patients destinated to a posterior stabilization procedure or to a closed reduction in order to exclude an eventual traumatic disc herniation. Although neither correlated with the severity of bone lesions nor with neurologic deficit, an unrecognized disc herniation may cause neurologic deterioration after surgery or closed reduction of fractures (Fig. 11) [61].

An acute posttraumatic disc herniation looks similar to degenerative disc herniation, but with the frequent association of parent disc and adjacent tissues injury signs. However, the definition of disc herniation needs to be modified in the presence of significant subluxation. In sagittal MR views, while the position of the posterior annulus is normally assessed relative to the posterior margins of both adjacent vertebral bodies, in case of sublussation the PLL is stripped away from the superior vertebra and the enlarged anterior epidural space may contain a relatively large disc fragment without it compressing the thecal sac. In the setting of traumatic sublussation, a disc herniation is a focal protrusion of disc material that extends posteriorly to a plane tangent to posterior cortical margin of the body below the subluxation, being this the only anatomic relation that remains costant, regardless of the dislocation severity (Fig. 6) [65].

Despite the advantages offered on soft tissues assessment, the indication for routine use of MRI in the clearance of spinal injuries remains debated. In a recent study most of treatment changes due to MR findings resulted from identification of spinal cord injury (81%) rather than the discovery of occult instability (19%) [66].

6. The neurological damage

About 11.000 spinal cord injury occur every year in US, 55% of which involve the cervical spinal cord [2]. Spinal cord injury (SCI) is a disastrous, often definitive and irreversible event which besides worsening the quality of life, also reduces life expectancy approximately to half of that in normal people.

Fig. 11. (a and b) Skier after a fall. CT midline reformatted scan showing hyperflexion trauma with anterior C5 dislocation. The patient being neurologically normal, did undergo a closed reduction. For the appearance of paresthesia a RM was performed. Sa sagittal midline STIR MR scan depicting a C5-C6 herniation associated to a focal epidural hematoma. Fact dislocation is an injury often complicated by traumatic disc herniations. A preoperative MR should always be performed before any treatment.

SCI represents also a great burden to individual as well as to the society. In US the lifetime costs of care for an individual averages $2 million, but vary widely according to the age, completeness, and level of injury. The global expenditure per year in US is about $6 billion for diagnosis, treatment and rehabilitation of patients. Furthermore, as 55% of all SCI occur in young adults between the ages of 16–30 years, the direct costs of management and care are flanked by indirect costs in terms of lost wages and productivity.

Among patients who survive, the most frequent neurologic deficit is incomplete tetraplegia (29,5%), followed by complete paraplegia (27,9%), incomplete paraplegia (21,3%) and complete tetraplegia (18,5%).

Central nervous system evaluation requires the highest priority following the airways and hemodynamic stabilization.

MR imaging is recommended in patients with persistent and worsening neurologic deficit and in case of suspect spinal cord compression, or epidural hematoma.

A low threshold for primary use of MRI is also indicated for injured rigid spine patients. Subjects with ankylosing spine disorders are prone to unstable spinal injuries, often complicated with SCI. The prevalence of SCI in rigid spines varies from 20% to 40% [67]. In the DISH patients, the ossification of PLL with spinal canal stenosis favours the neurologic damage, the likelihood and severity of which are more correlated to the length of the ankylosed segment than to the trauma severity. The diagnostic delay of injuries, due to insufficient imaging or non-recognition of symptoms (minor traumas in patients who already suffer pain), occur in up to 50% of cases in AS and DISH and also increases the likelihood of neurologic damage.

Neurologic status is the most important indicator of the severity of any spinal column injury and may be the single most influential predictor of treatment [14]. Significant neurologic injury can in fact occur and require surgical treatment even in the absence of any bone or soft tissue injury or overt instability [14].

Despite its absolute relevance, neurological status is accounted for only in the most recent classification schemes and severity scores including imaging and clinical features. In the SLIC system the score of neurologic function includes 0 (normal), 1 for nerve root compression, 2 in case of complete cord injury, and 3 corresponding to an incomplete cord injury, while 4 is assigned in case of incomplete cord injury with

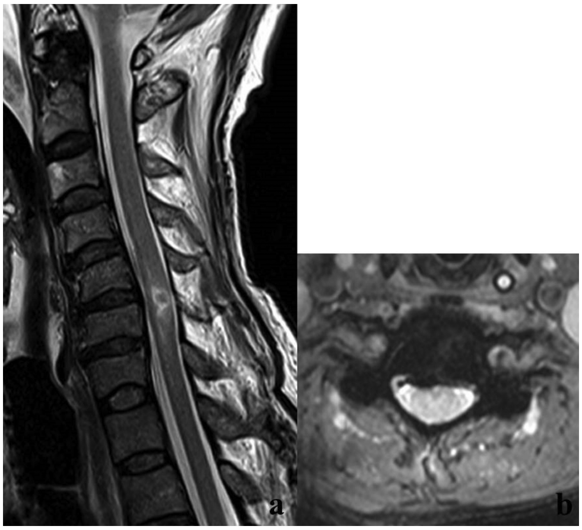

Fig. 12. (a and b) Hypeflexion trauma with spinal cord contusion. Midsagittal FSE T2-weighted MR image (a) depicting spinal cord edema spanning over two segment a C5-C6 centered by a little hypointense spot of hemorrhage (Bondurant grade 4 lesion) [68]. On axial GRE-T2*-weighted scan (b), the edema does involve the entire cross section of cord with little hypointense spots inside (Basic grade 4) [76].

ongoing cord compression. This is the most urgent condition where the patient's clinical outcome can be improved considerably with early surgery for limiting secondary damage.

Similarly, within the AOSpine classification, neurological status is graded in 6 levels varying from N0 (normal) up to N4 (complete spinal cord injury), with N1 indicating transient neurologic deficit resolving within 24 h and NX deserved for obtunded and unreliable patients.

The greatest impact of imaging on traumatic pathology of the spine, as a whole, has been the direct visualization of spinal cord by MR. MR imaging has a critical role in the assessment of SCIs in which it show lesion location, extent and severity.

Bondurant et al described four patterns on MRI, including: normal cord (1), one-level edema (2), multi-level edema (3), edema plus hemorrhage (4) (Fig. 4) [68]. The tipical SCI lesion on MRI is a spindle-shaped lesion with a center of hemorrhage surrounded by edema spanning in rostral-caudal direction (Fig. 12). Bondurant classification systems have been shown to correlate with injury severity and to supplement clinical measures for predicting clinical outcome [69,70].

Several studies have found correlation between MR findings of SCI, clinical presentation and outcome. While all patients with no spinal cord lesions at MR recover completely, the site, type, and extension of spinal cord lesions not only correlate with the neurologic deficit at presentation, but also are predictive of functional recovery at follow-up. [61,68,71].

Posttraumatic spinal cord hemorrhage is a discrete focus of hemorrhagic contusion developping for rupture of mìicrovasculature within the central gray matter at the point of mechanical impact. It represents most often a hemorrhagic necrosis than a pure hematomyelia [68].

The level of hemorrhage corresponds exactly to level of neurologic injury. The presence of spinal cord hemorrhage is always clinically relevant. A focus spanning over 10 mm in length often implies a complete and definitive neurologic injury (ASIA A), while a hemorrhage less than 4 mm in length is not associated with complete SCI and shows a better prognosis). Marciello compared the evolution of neurologic deficits as changes of individual motor scores in 24 subjects, with or withour spinal cord hemorrhage. In patients with hemorrhage only 16% of upper extremities muscles and 3% of lower extremities muscles improved to an useful grade (> 3/5), versus 73% and 74% of corresponding muscles with no hemorrhage [72].

Concordingly, a more recent study by Bozzo et al, found that 95% of patients with hemorrhage in the cervical spinal cord did remain ASIA A, with 5% improving of one grade only.

Owing to local hypoxia/hypoperfusion inside an injured cord, deoxyhemoglobin persists for a prolonged time (8 days or more) accounting for a permanent T2 hypointense signal reflecting a susceptibility-related T2-shortening. On susceptibility weighted imaging (SWI), the mean signal ratio of hemorrhage to normal tissue is lower than that on T2*weighted imaging. Thanks to a more sensitive detection of microbleeds multishot SW imaging can improve evaluation of the prognosis for SCI patients and should be imployed in the routine evaluation of cervical SCI patient.

While hemorrhage is always flanked by edema, edema alone may develop.

In comparison to hemorrhage, edema subtends a better prognosis. However, the longitudinal extent of edema has clinical influence and prognostic relevance. While patients with one-level spinal cord edema improve on average 1,9 ASIA grades, multilevel edema subjects do only 0,9 grades [73].

The evolution over time of cord lesions influences their appearance depending on the delay between the injury and imaging and must accounted for in order to improve the prognostic prediction.

Depending on the SCI severity, the rate of expansion of the intramedullary lesion in cervical SCI ranges from 200 μm/h in AIS grade C patients to 900 μm/h in AIS grade A and B patients.

Leypold et al studied the initial evolution of both cord edema and hemorrhage and found edema to have a dynamic evolution, expanding to a rate of one-vertebral-level for every additional 1,2 day betwen injury and MRI. In comparison, hemorrhage evolves faster and riches a plateau early, then appearing more static [74].

In comparison to hypointensity of hemorrhage, T2 hyperintense signal is less specific and reflects a combination of vasogenic edema, cytotoxic edema, axonolysis, myelinolysis, inflammatory cellular infiltrate, and microhemorrhage. While the conventional MRI cannot distinguish cytotoxic from vasogenic edema, the former may be directly depicted by diffusion weighted imaging (DWI) as hyperintense area at center of trauma.

T2 hyperintensity and cord swelling reflects the secondary damage.

Flanders et al assessed the effects of location and length of hemorrhage and edema on changes in the values of the motor scale of the functional independence measure (FIM) assessed on admission to and discharge from rehabilitation on 49 patients undergoing MR within 72 h after a SCI. The Authors found that hemorrhage, long segments of edema, and high cervical locations are MR findings predictive of functional recovery [70]. The importance of this work is that FIM scale provide a standard measure of disability and a more comprehensive evaluation of residual patient's capacity of performing daily tasks in comparison to single motor tests.

Aarabi et al conducted a retrospective study to identify potential indicators of AIS grade conversion in patients with cervical SCI who underwent surgical decompression. Through an univariate analysis the Authors showed that age, injury mechanism, injury morphology, steroids, timing of decompression, and surgical technique of decompression had no significant relationship with AIS grade conversion. Intramedullary lesion length (IMLL) was the only and the strongest predictor of AIS grade conversion. Related to IMLL, the completeness of decompression of the spinal cord on postoperative MRI, as assessed by the presence of CSF around the lesion, also appeared to influence grade conversion [75].

Even though the cord damage has been traditionally measured and classified on MR sagittal imaging, the longitudinal extent is just an aspect of any cord lesion. Among the different abnormalities appearing on MR sagittal T2-weighted images, while the absence of lesions and the hemorragic pattern are the most accurate predictors of outcome, multilevel edema associates to a wider variety of ASIA Impairment

Scale (AIS) grades, at presentation and at time of hospital discharge [73]. As the longitudinal extent of injuries and the Boundurant classification not always reflect the full spectrum of acute spinal cord injuries, one study on 60 patients by Talbott et al for the first time evaluated SCIs on the axial plane. The Brain and Spinal Injury Center (BASIC) scheme is a 5-point ordinal scoring which classifies the severity of an acute SCI based on the transverse extent of signal abnormalities as qualitatively assessed on axial T2-weighted MR images centered at the lesion epicenter [76]. The BASIC score encompasses the whole spectrum of SCIs including: absence of any abnormality (BASIC 0), T2 hyperintensity confined within the gray matter (BASIC 1), hyperintensity beyond the expect margins of gray matter (BASIC 2), hyperintensity on the entire cross area of spinal cord (BASIC 3), axial hypersignal with superimposed hypointense hemorrhage (BASIC grade 4) (Fig. 12) [76]. Among patients with multilevel edema (Bondurant's grade 3), the BASIC score could distinghuish grade 2 lesions with some spared white matter, from grade 3 lesions with diffuse transversal signal changes, whose outcomes were significanly different. While 88% of BASIC Score 2 patients achieved an AIS grade of C or D at hospital discharge, 67% of BASIC Score 3 patients were discharged with AIS Grade A or B [76]. The BASIC classification indicates the functional relevance of anatomically spared white matter in SCI patients. Several preclinical studies have also demonstrated that the transverse extent of an SCI and white matter involvement are major determinants of functional outcomes and better correlate with functional recovery than longitudinal measurements.

Animal studies also indicate that conventional MR techniques do not accurately demonstrate the cord damage and this flaw depends on the failure to demonstrate functionaly spared **white** matter.

Advanced MR imaging, and particularly diffusion-weighted techniques, are able to assess the integrity of spinal cord **white** matter [77].

Diffusion-weighted imaging (DWI) employs free water proton diffusion as a contrast-determining parameter. Diffusion-tensor imaging (DTI) depicts the 3-D microstructural anatomy and directional arrangement of WM fibers by measuring the anisotropic diffusion of water inside in multiple different directions, by directional and magnitude vectors (Fig. 13).

Myelinated axons preferentially diffuse water along their long axis as relative anisotropy resulting in a high longitudinal apparent diffusion coefficient (lADC) and a low transverse apparent diffusion (tADC) coefficient. Fractional anisotropy (FA) also describes the relative directionality of molecular motion of water and is a marker of both axonal density and myelin content. Axial diffusivity (AD) and radial diffusivity (RD) depend on the integrity of axons and myelin, respectively.

As any trouble of integrity and arrangement of WM cord fibres generates isotropic water motion, DTI parameters become surrogate markers of WM integrity or damage and can evaluate axonal status quantitatively (Fig. 13) [77].

SCI shows increased tADC and decreased lADC also in normal-appearing WM and can document the true extent of injury improving the correlation between the neurologic deficit and MR imaging by integrating morfological data. ADC and FA values are both reduced at injury site probably due to cellular and axonal swelling, mainly in case of hemhorrage, reflecting the severity of injury. In nonhemorragic SCI DTI parameters strongly correlate with the initial motor scores. Changes over time of AF and ADC can reflect the effects of neuroprotective agents and remyelination processes and can predict functional recovery.

Newer diffusion techniques, such as diffusion kurtosis imaging (DKI) and Q-space MRI, give other information about normal and pathologic tissue. DKI evaluates tissues microstructure through the analysis and quantiffication of the modification produced on isotropic and Gaussian water diffusion by tissue barriers and compartments.

Q-space technique assesses the diffraction patterns and water displacement profiles by measuring diffusion within a range of a few microns and infer the structural integrity of spinal cord at the cellular level resolution.

Faster techniques such as parallel imaging which reduce the effects of physiologic motion and multiarray coils which improve the signal-to-noise ratio have improved image quality and measures accuracy.

The Signal Enhancement by Extravascular water Protons (SEEP) technique has also been used for functional MR (fMR) studies on the spinal cord with tasks. This technique is based on the principle

that the neuronal activation leads to transfer of water from intravascular to extracellular space. fMRI may demonstate residual motor neuronal activity distal to lesions and have a potential role for guiding rehabilitation [78].

DTI changes of cortico-spinal tracts can also occur and probably reflect supratentorial centers reorganization after SCI.

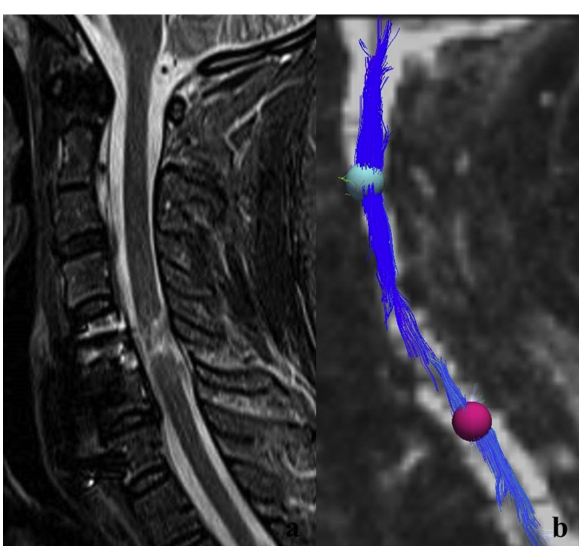

Fig. 13. (a and b) 31- year-old male after car accident. C5-C6 luxation with paraplegia and T5 anesthesia. Fixation at 24 h. Bilateral forearm flexion but no finger movements bilaterally. STIR –T2-weighted midsagittal MR image (a): Bondurant grade 4 spinal cord. DTI through a two ROIs approach showing some spared fibers across the lesion (b). Courtesy of Professor Roberto Gaspararotti, Neuroradiology, Spedali di Brescia (IT).

7. Conclusions

CT and MRI play complementary roles as imaging modalities for the evaluation of the traumatic cervical spine, in acute setting. MDCT is the first-line imaging modality being rapid, easily performed, and optimally depicts bone anatomy and fractures.

MRI provides unmatched soft tissue delineation for the assessment of the discs, ligaments, and spinal cord. According to actual spine trauma classification schemes which account for the patient's neurological status MR is the modality of choice in any patient who has persistent neurologic deficit after spinal trauma. Another indication is persistent pain in case of a inconclusive CT.

In patients with presumed SCI MRI may disclose the location and severity of the injury and depict the cause of spinal cord compression, in particular in patients with incomplete SCI, for whom surgical intervention can prevent further deterioration.

The potential risks of transporting an unstable patient must everytime be weighted against the benefits derived from the diagnostic information MRI can give.

Advanced techniques, such as DTI, provide microstructural information about the axonal and myelin integrity and can integrate the information coming from conventional sequences to improve outcome prediction and monitoring of therapies.

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Conflict of interest

All authors have read the manuscript, they approved this submission and declare that they do not have any conflicts of interest related to this work.

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