High Traumatic Energy Related
Spine Injuries and Spinopelvic dissociations

Ph.D. thesis

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List of Abbreviations

ABCDE – Airway, Breathing, Circulation, Disability, Exposure

ALL – Anterior Longitudinal Ligament

ANOVA – ANalysis Of VAriance

AO – Arbeitsgemeinschaft für Osteosynthese

AS – Ankylosing Spondylitis

ASIA – American Spinal Injury Association

ATLS – Advanced Trauma Life Support

BASE-jumping – Building, Antenna, Span, Earth-jumping

CBT – Cortical Bone Trajectory

CPR – Cardio Pulmonary Resuscitation

CT – Computed Tomography

D/BME – Disc/ Bone Marrow Edema

DE-CT – Dual-Energy-Computed Tomography

DISH – Diffuse Idiopathic Skeletal Hyperostosis

FAST – Focused Assessment with Sonography for Trauma

FN – False Negative

FP – False Positive

ICU – Intensive Care Unit

ISS – Injury Severity Score

kVp – kiloVoltage peak

LODOX – LOw DOse X-Ray

MRI – Magnetic Resonance Imaging

NM – not mentioned

NPV – Negative Predictive Value

OLF – Ossification of the Ligamentum Flavum

OR – Operating Room

PEA – Pulseless Electrical Activity

PLL – Posterior Longitudinal Ligament

PPV – Positive Predictive Value

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analysis

PSF – Posterior Spinal Fusion

RIVA – Ramus InterVentricularis Anterior

SI – iliosacral screw

STIR – Short Tau Inversion Recovery

TF – Triangular Fixation

TIRM – Turbo Inversion-Recovery Magnitude

TN – True Negative

TP – True Positive

TSF – Transverse Sacral Fracture

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1. Introduction

Spine injuries can lead to a devastating outcome especially if neurological impairment is present. Although most of the fractures are related to osteoporosis, or motor vehicle accidents if related to high energetic mechanism. Rather uncommon however, likely underreported spine fractures are related to extreme sports such as airborne sports. Because of its landscape, Switzerland became highly important where people come from all over the world to do for airborne sports. In this thesis we want to highlight the relationship between spine injuries as well as spinopelvic dissociations and airborne sports and report the current diagnostic algorithm and subsequently treatment. In addition, because of the uncommon injury pattern of spinopelvic dissociation we performed a systematic literature review to compare the standards in treatment and were interested if a new diagnostic tool – the Dual-Energy-Computed Tomography – would allow higher accuracy and be beneficial in the initial diagnostics.

The spine consists of 24 vertebral bodies plus the sacrum. This includes seven cervical, twelve thoracic and five lumbar vertebral bodies. The vertebral bodies resist compressive forces acting down along the axis of the spine. Hereby, the stability is provided by the trabeculae and the outer cortical bone [1]. To resist higher forces during forward bending, the anterior cortex is thicker and less porous than the posterior one [2]. The endplates consists of cortical bone, of which the caudal one is thicker compared to the cranial one. In addition, it is supported with less dense trabecular bone [3], [4], [5]. The intervertebral central regions are covered with the intervertebral disc made up of thin hyaline cartilage. It is only weakly bonded to the bone and therefore allows spreading the compressive loading along the endplates [6], [7], [8].

The posterior neural arch is essential to protect the spinal cord and serves as attachment for ligaments and muscles [9], [10]. The discoligamentous complex consists of the posterior and anterior longitudinal ligaments as well as the posterior ligamentous complex which comprises of the flavum-, interspinous, and nuchal ligaments [11], [12].

For stability, the spinous processes can resist a proportion of the compressive forces, the apophyseal joints are the main stabilizers. In the lumbar spine these resist approximately 20% whereas the apophyseal joints in the upper spine only resist half as much [13]. For the prevention of excessive lumbar flexion, the most important structures, are the intervertebral ligaments which span adjacent the neural aches [14].

The sacrum allows the comminution between the pelvic ring and the vertebral column. This transition is called spinopelvic motion which is defined as the difference between standing and sitting sacral slopes.

1.1 Spine Injuries

Spine injuries result mainly from a direct trauma onto the vertebral column or axial compression. Hereby, it has to be differentiated between vertebral fractures and/ or discoligamentous injuries. Latter one rather occurs especially in high traumatic energetic accidents, such as car accidents or falls from high height and maybe accompanied by other diseases such as the diffuse idiopathic skeletal hyperostosis or spondylitis ankyolosans.

Because of the spines' nature and its bone mineral density, which decreases with age, it is vulnerable to compression. Compressive forces typically act along the axis of the spine, perpendicular to the mid-plane of the intervertebral discs [15]. In falls from height a compressive overload may result on the disc and the underlying vertebral body. This can cause a cranial endplate fracture since it is weaker and thinner than the caudal one. Especially the lumbar spine is reported to be the weak link in the spine [16], [17], [18], [19]. The higher the energy impacts on the nucleus pulposus, the more compressive stress acts onto the annulus [20]. In combination with a spinal flexion an overload can result in a crush fracture. In accidents with shear, bending and torsional forces a much wider range of fractures can be sustained [21], [14].

Discoligamentous injuries can either result in addition to a vertebral fracture or isolated. Typically, anterior longitudinal ligament ruptures occur in hyperflexion injuries which can, in rare occasions, be accompanied by posterior longitudinal and posterior ligaments complex injuries. More often a combination of anterior and posterior ligament injuries are observed in translational injuries [22], [23], [24], [25].

Another injury which affects the transition zone between the lumbar spine, sacrum and the pelvis is called spinopelvic dissociation. It was first described by Purser et al. in 1969 followed by Roy-Camille et al. in 1985 [26], [27]. This fracture pattern was called suicidal jumper's fracture initially which was renamed to spinopelvic dissociation later on [28], [29]. Spinopelvic dissociation is typically of U-, Lambda-, or T-shape with a transverse fracture at the S1/S2 disc space or S2 vertebral body, extending into bilateral vertical sacral fracture lines. Hereby, the lower sacral segment and the pelvic ring separates from the upper central segment of the sacrum which results into an osseous dissociation between the sacrum respectively pelvis and vertebral column [30]. The term 'spinopelvic dissociation' shall enable to differentiate between lumbosacral fracture dislocation or bilateral iliosacral joint dislocation [29]. Because of the high energetic accident and the change in pelvic incidence from change in flexion or extension, the posttraumatic mismatch between pelvic incidence and lumbar lordosis may affect the global sagittal alignment of the spine if not properly reduced [28].

Sacral fractures typically result from multi-directional forces acting on the lumbopelvic junction and therefore a combination of different forces [31], [32]. The position of the lumbar spine at the time of axial impact is most important [27]. In simultaneous kyphosis of the lumbar spine, anteriorly directed force vectors occur which causes flexion type spinopelvic dissociation classified as Roy-Camille type 1 and 2. On the other side, in patients with a lordotic lumbar spine during axial impact, extension type injuries occur which are described as Roy-Camille type 3 [27].

The most common complication of spine injuries and spinopelvic dissociations is dural tears as well as neurological impairment. Especially in spinopelvic dissociation, the incidence of neurological deficit is described of up to 94 and 100% of cases [33], [34]. Other complications may include soft tissue injuries such as a Morel-Lavallee lesion and further concomitant injuries [35].

1.2 Epidemiology

The most affected regions of spine fractures are located in the thoracic and lumbar regions with an estimated incidence of 700,000 fractures in the United States each year [36], [37]. Main causes of spinal and sacral injuries include osteoporotic fractures in elderly patients as well as high-energy traumatic injuries such as motor vehicle accidents. In latter ones the mean age of patients is reported with 45.7 years with a male predominance in 65.5%

of cases [38]. These fracture patterns have a major impact on death and disability in young adults such as neurological impairment and concomitant injuries [39], [40]. Incidences of spine fractures vary from 8,000 to 16,000 cases per year in the United States and for transverse sacral fractures between 3% to 5% of all sacral fractures [29], [41], [42]. The exact incidence of discoligamentous injuries of the spine remains unknown, however in the cervical spine approximately 0.34% of all injuries are accompanied by ligamentous injuries [43]. Only 2.9% of sacral fractures are pelvic disruptions associated with U-shaped or H-shaped sacral fractures [44], [28]. Typical causes include fall from high heights, high risk sports as well as motor vehicle accidents [45].

In terms of sports related spine fractures winter sports are the most common ones followed by mountain biking, contact sports (i.e. martial arts, American football) [46], [47]. Rather uncommon and likely underreported extreme sports include airborne sports which consists of Paragliding, Speedflying, Parachuting, Delta flying and BASE jumping [48], [49].

Because of Switzerland's landscape airborne sports are very popular of which Paragliding is the most popular one. One of the most famous venues for these sports is Lauterbrunnen (Berne, Switzerland), where approximately 15,000 jumps and flights are performed annually [50], [51], [52].

1.3 Paragliding

In the following a short overview of paragliding is given which is the most common and traditional airborne sports; thus, it contributes to the overwhelming majority of injuries and is partly similar to other aerial sports including Speedflying, Delta Flying, Parachuting and BASE-jumping. Since BASE-jumping, Parachuting and Delta Flying are primarily related to high falls especially casued by pilot errors, Paragliding requires knowledge on the thermic and the parachute itself to understand the potential risks and causes of falls.

Paragliding is related to the ram-air parachute which was invented for the military and developed by Domina Jalbert in 1964 [53]**.** This can be performed alone or in a tandem likewise Skydiving. For this, a wing, lines and risers, harness, a reserve parachute as well a helmet are required. The parachutes are of elliptical-shape and persist of multi cells which can be controlled for lateral glide. It is of light weight without any rigid primary structure. At the front, the parachute contains a leading edge with cell openings and at the back the trailing edge. This allows an air flow when inflating the canopy with a higher pressure on the bottom of the glide than of the top. A whole lot of lines are attached to the parachute and allow to control and break it by the pilot.

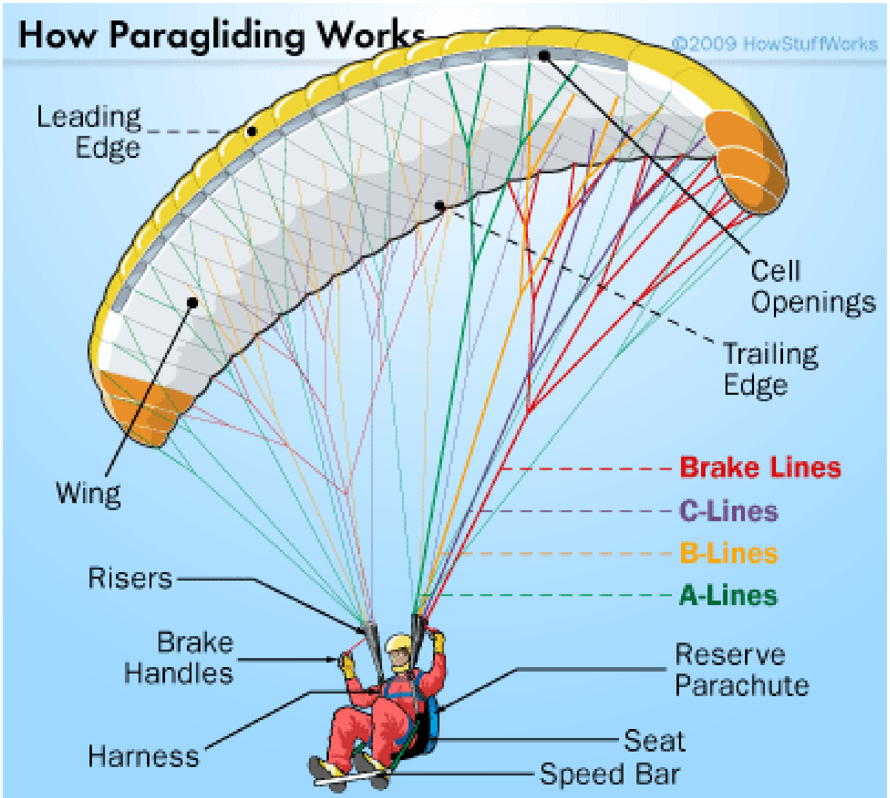


Figure 1: Components of a parachute [53]

The parachutes are potentially aerodynamically unstable and only stable in calm air because of a low center of gravity. Possible rising air types are thermals, ridge lift and wave life. In thermal condition the hot air rises from the ground, whereas in ridge lift the air blows against mountains moving it upward, allowing a lift along its slope. The third type – wave lift – is equivalent to ridge lift at the beginning, however, turns into a downwind on the other mountain side. This condition may only occur in strong winds. In calm air the pilot tries to balance out the pendulum system of the parachute controlling the parachute effectively.

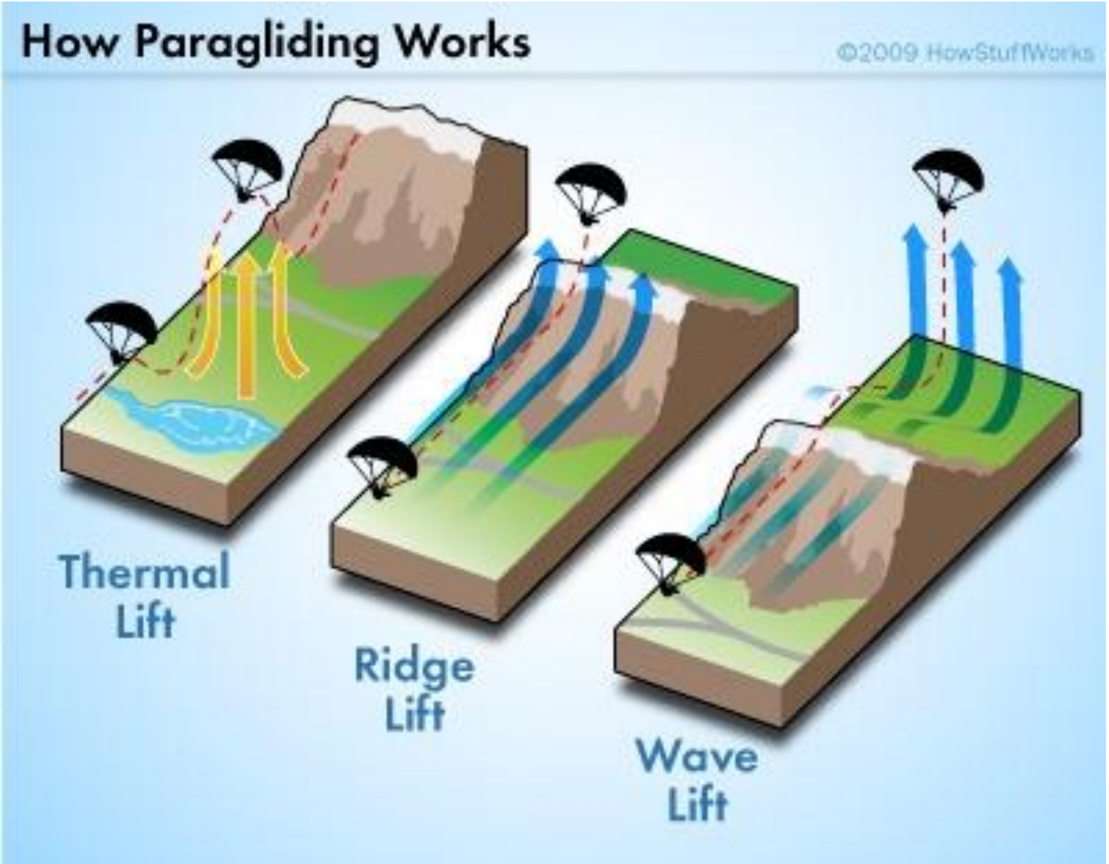


Figure 2: How Paragliding works [53]

The highest risk for pilots is when the parachute is collapsing. This may occur when the canopy pitches forward because of an insufficient angle of attack. In this situation the break must be pulled to anticipate the effect. Additionally, the pilot has to balance out the pressure up to restore it. Speedflying is an advanced technique of paragliding where smaller parachutes are used. These allow quicker descends from height however are potentially more unstable. If the pilots are unable to control and stabilize the parachute in speedflying or paragliding, due to lack of experience or a collapsed parachute, they are likely to fall completely uncontrolled and trying to land on the feet causing high forces primarily on the spinopelvic junction. Typically this occur during the landing from rather lower height.

In contrast to skydiving where participants jump out of a plane of helicopter, BASE-jumpers typically jump from a fixed object such as a mountain. Hereby, the majority of BASE-jumpers have only one parachute which leads to devastating and highly severe injuries if the parachute cannot be opened. Then the pilots typically from higher heights without slowing down. Those pilots who survive try to aim for a forest or trees which can slow the fall down.

Delta-flying or also Hang gliding requires wing made of aluminum alloy or composite frame covered with synthetic sailcloth. The pilots hang below the frame in a harness and controls the wing by shifting body weight. The athletes do not have a parachute and start from a mountain, hill, cliff or raised terrain. The wings are designed to resist high bending and flex forces providing favorable dynamics. For landing the glider has to be stalled which tips up the nose which allows the pilot to land the feet. As this one provides a stable frame no emergency parachute is required and most accidents are related to the landing procedure at a too high speed.

1.4 Trauma management

Because of Switzerland's landscape a well-established air rescue system was developed with an emergency physician on board which allows early rescue and immediate admission to the hospital while providing maximal pre-hospital treatment. This may potentially increase the survival rate and prevent from further complications. Although this air rescue system was established for the trauma management, the majority of missions include strokes and heart attacks. Only a small percentage of helicopter missions (4.9%; n=544/11,055 in 2016) are related to traumatic injuries [54].

Once the patients are found and rescued they are admitted to the hospital. In Switzerland the largest university hospital is the university hospital Berne. It is a major level I trauma center and its emergency department consists of four helicopter spaces and three resuscitation rooms. The catchment area includes approximately 1.5 million people living in a 10,000 km^2 area for selected patients such as polytraumatized ones or uncommon suspected injuries including spinopelvic dissociation [55].

1.4.1 ATLS Algorithm

Patients with ISS equal or greater to 16 are initially examined in the resuscitation room. The clinical examination is performed according to the Advanced Trauma Life Support (ATLS) following the ABCDE principle as shown in figure 3 after treating the most obvious injuries, such as arterial bleeding by compression or using a tourniquet. If resuscitation is required, all reversible injuries (5 H's and 5 T's) must be identified which may cause a pulseless electrical activity (PEA) situation as this is the most common cause of death in polytraumatized patients [56], [57].

In intubated patients, if no life-threatening circumstances are found a wake up attempt should be performed.

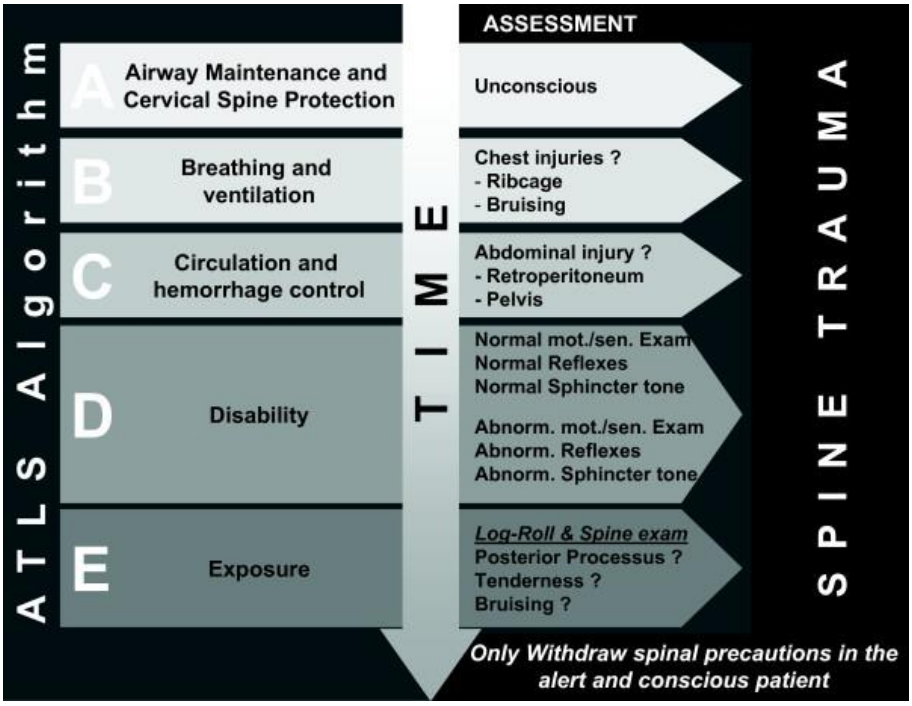


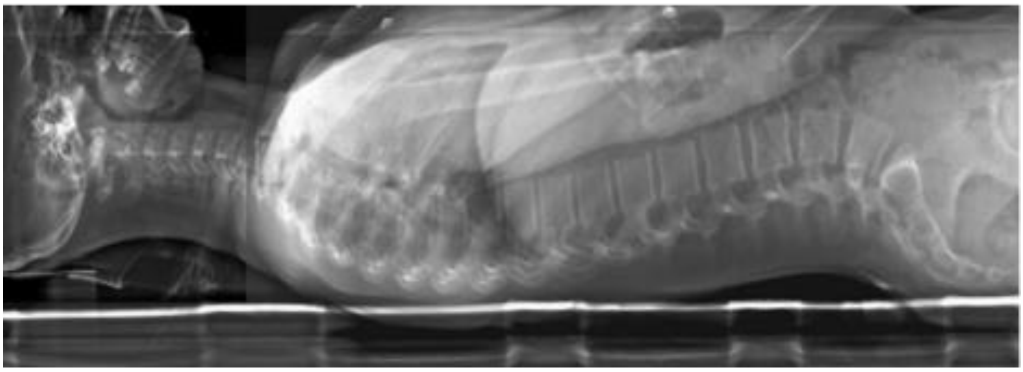
Figure 3: ATLS Algorithm [58]

1.4.2 Diagnostics

Besides clinical examination several adjunctive tools are used. These include either plain chest and pelvis radiographies or whole body anteroposterior LOw DOse X-ray (LODOX), focused assessment with sonography for trauma (FAST) and full body computed tomography (CT) [25]. The LODOX is a whole body X-ray which replaces the conventional thorax and pelvis X-ray. This fastens the diagnostics and allows an overview for any potential life-threatening diseases such as pneumothorax, pelvis, spine or extremity fracture (Figure 4).

Figure 4: LOw DOse X-ray scan and radiographic imaging [59]

a)



b)

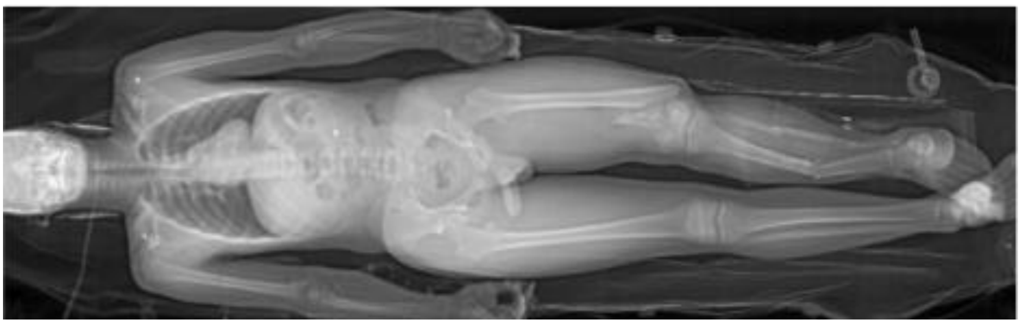


Figure 5a) LODOX whole body lateral and b) antero-posterior radiography [60]

The FAST assesses free fluid in the Morison – hepatorenal recess –, Koller – splenorenal recess –, Douglas pouch – between rectum and uterus for women respectively rectum and urine bladder for men – and pericard to exclude a tamponade. Additionally, the extensive FAST allows to exclude pneumothorax by visualizing the sliding lung between the pleura parietalis and visceralis. The different locations of the focus assessment with sonography for trauma is shown in figure 6 [61].

A) B)

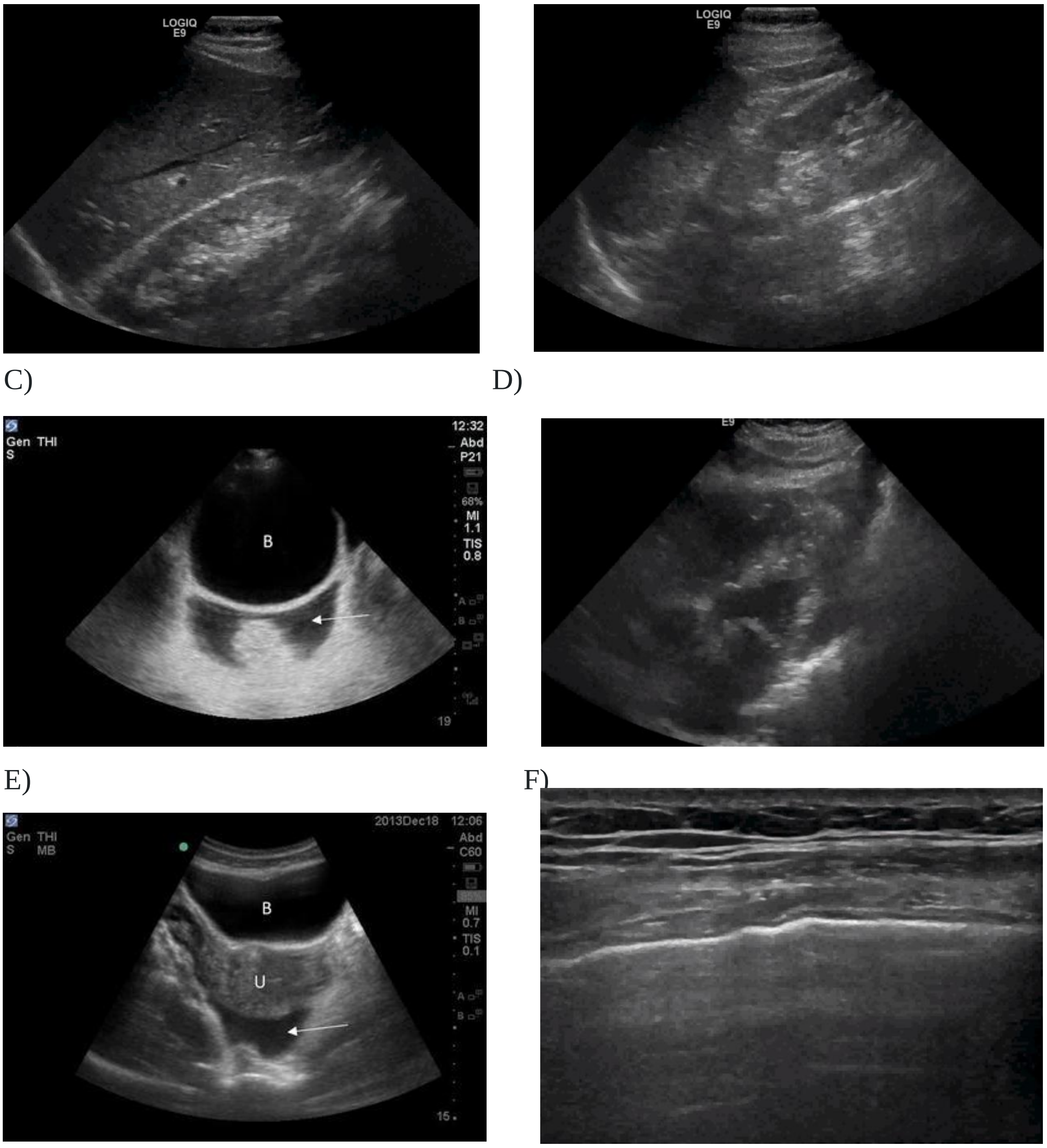


Figure 6: Normal findings in FAST A) Morison Pouch; B) Koller Pouch; C) pathologic Morison Pouch in male, respectively E) female patient; D) normal four-chamber view of the heart; F) normal sliding lung view [61], [62]

The following procedure depends on the general condition of the patient and the findings in the focused assessment with sonography in trauma. If the patient is stable and an acute abdominal bleeding is identified in FAST a CT should be performed, whereas in unstable patients an emergency surgery is indicated. This was summarized by Pace et al. in figure 7 [62].

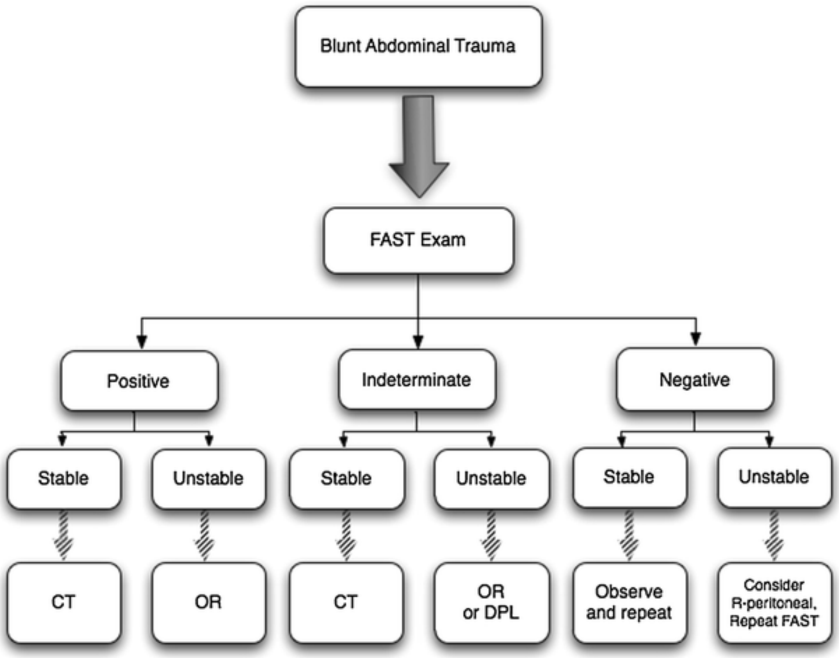


Figure 7: Algorithm after FAST examination in abdominal trauma [62]

After the clinical assessment plain radiography or LODOX as well as focused assessment with sonography in trauma, a computed tomography is performed to identify any further injuries and to obtain more information. Although in some hospitals the CT is placed in the resuscitation room, according to the current guidelines, only in stable patients a scan should be performed.

In rare occasions where a discoligamentous injury is suspected and/or neurological deficit is observed, magnetic resonance imagining (MRI) may be used as a further adjunctive tool to assess spinal cord and ligamentous injuries. New alternatives for MRI are the Dual-Energy-Computed Tomography (DE-CT) which have shown promising results and were further investigated in this thesis [63]. Therefore, a special computed tomography respectively a special software module is required which uses two scintillation layers (two sources of x-ray), one normal and a second less powerful x-ray with two corresponding detectors. In rapid kVp switching, the tube voltages follows a pulsed curve which is collected twice for every projection at high and low tube voltage. The two scintillation layers enable a separation between the high and low energy spectra [64]. This allows to provide further information about the tissue composition, artefact reduction and optimizes images and detect bone marrow edema accurately and allow information about the potential involvement of the vertebral disc and/ or collagenous structures including tendons and ligaments likewise the MRI [63]. Major advantage is the availability and speed of the scan in comparison to MRI which can also be performed in patients with magnetic implants like a pacemaker which is mostly unknown in polytraumatized patients.

If clinical examination reveals only minor injuries, patients are transferred to the general ward. In unstable patients' emergency surgical interventions including thoracic, ventricle drainage insertions as well as pelvic external fixation are performed in the resuscitation room. All other procedures such as pelvic packing, external fixation of long bones or thoracotomy are performed in the operating room. If no surgery is required and patients are still potentially unstable, they are transferred to the intensive care unit.

1.5 Classifications

For the injury severity the most common classification used is the injury severity scale, which scales between 1 and 75, where 75 indicates unsurvivable [65]. For calculations, the three most severe injuries are used and added up by square of each individual injury. Therefore, the body is divided into different regions including (1) head and neck, (2) face, (3) chest, (4) abdomen or pelvic content, (5) extremities or pelvic girdle and (6) external injuries. In each region the severity is rated between 1 as minimal injuries and 6 unsurvivable. If any individual value is 6 the score is automatically to 75.

For detailed documentation of spine injuries a variety of different classifications can be used. Spine fractures can be classified according to the Magerl- and/ or AO-Spine-Classification. The more recent AO-Spine classifies the indeterminate injuries to the tension band in addition to the fracture pattern which require further radiographic diagnostics including magnetic resonance imaging or Dual-Energy-Computed Tomography (Figure 8) [66], [25], [67], [65].

The vertebral body fracture patterns are categorized into minor, non-constructural fractures, wedge-compressions, split, incomplete or complete burst fracture before indicating discoligamentous injuries resulting in posterior wall structure involvement and/ or rotational instability (B or C type). Furthermore, the subcategories describe no significant injuries to the spine (fractures of the facet joint) – A0 –, wedge or impaction (A1), split or pincer fracture (A2), incomplete or complete burst fracture (A3 respectively A4), pure transosseous disruption (B1), osseoligamentious disruption (B2), hyperextension fracture (B3) and finally translational deformity as type C fracture. The modifiers describe the suspected presence of posterior capsuloligamentous complex injuries without complete disruption (M1), critical disk herniation (M2), stiffening, metabolic bone diseases including DISH, M. Bechterew, AS, OLF (M3) and vertebral artery abnormality (M4). This allows to categorize an assumption which may be finally confirmed or excluded intraoperatively.

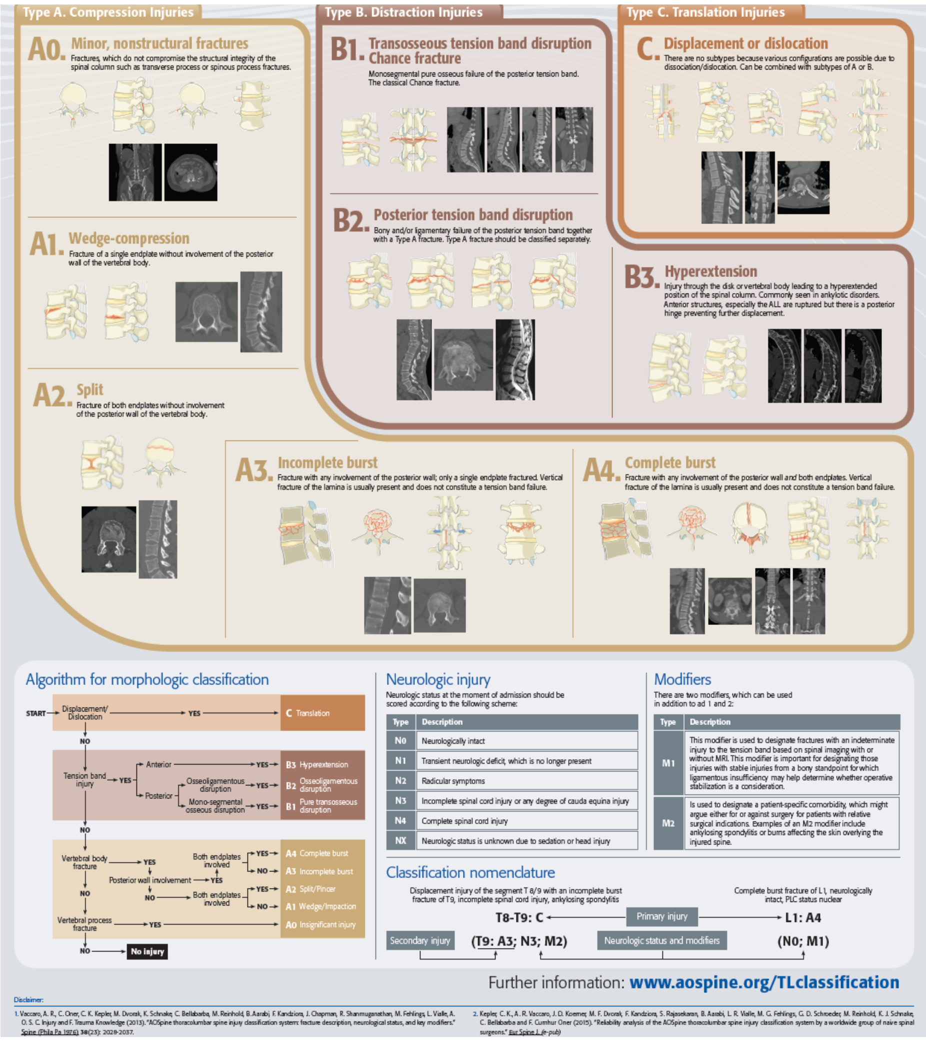


Figure 8: AO Spine classification [66], [67], [68]

On the other side spinopelvic dissociations are classified according to the Roy-Camille and Denis classification. The topographical relation of Denis Zone III and the horizontal fractures can be further divided into 'U', 'H', 'T' and 'Y' shape as illustrated in Figure 9, 10 [29], [31]. Further one patient with a U-type fracture is illustrated in Figure 11.

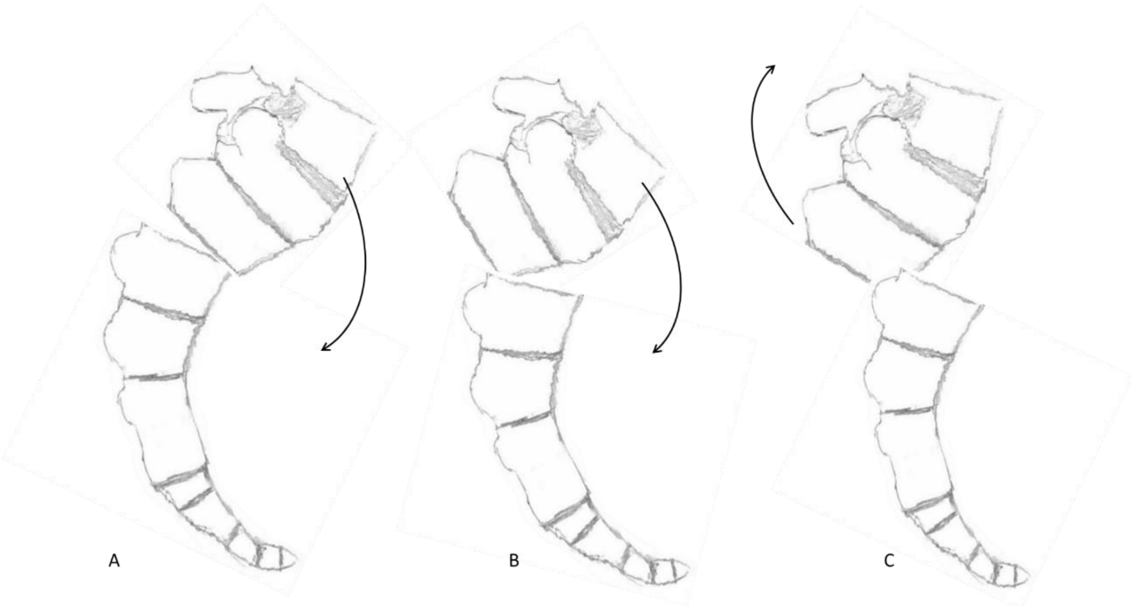


Figure 9: Roy-Camille classification [69]

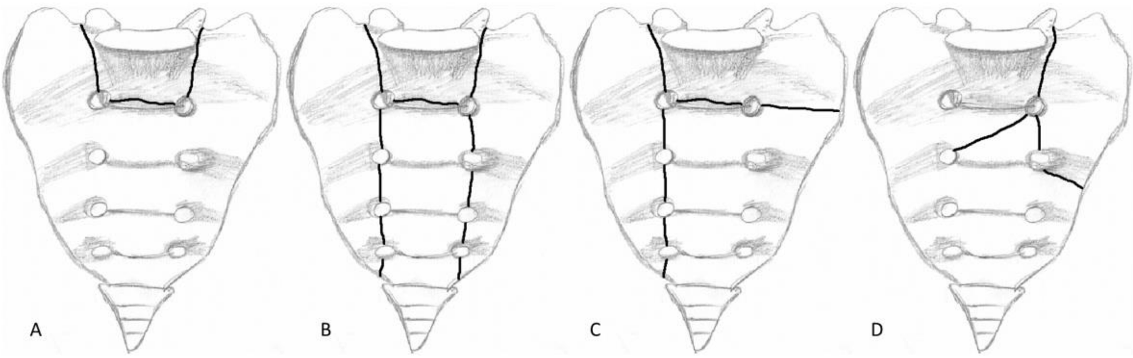


Figure 10: Denis zone 3 classification as U-, H-, T and lambda shape fractures [69]

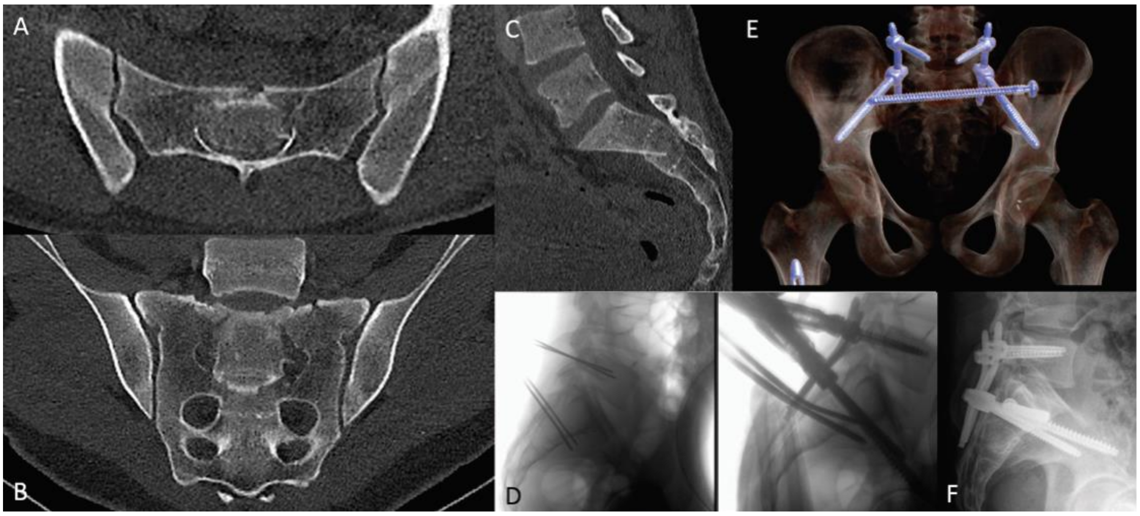


Figure 11: U-type fracture before and after reduction and triangular fixation [70]

Likewise spine fractures, sacral factures can be classified according to the AO-Spine classification. Spinopelvic dissociation are defined as B4 or C type fractures which are unstable (Figure 12) [71].

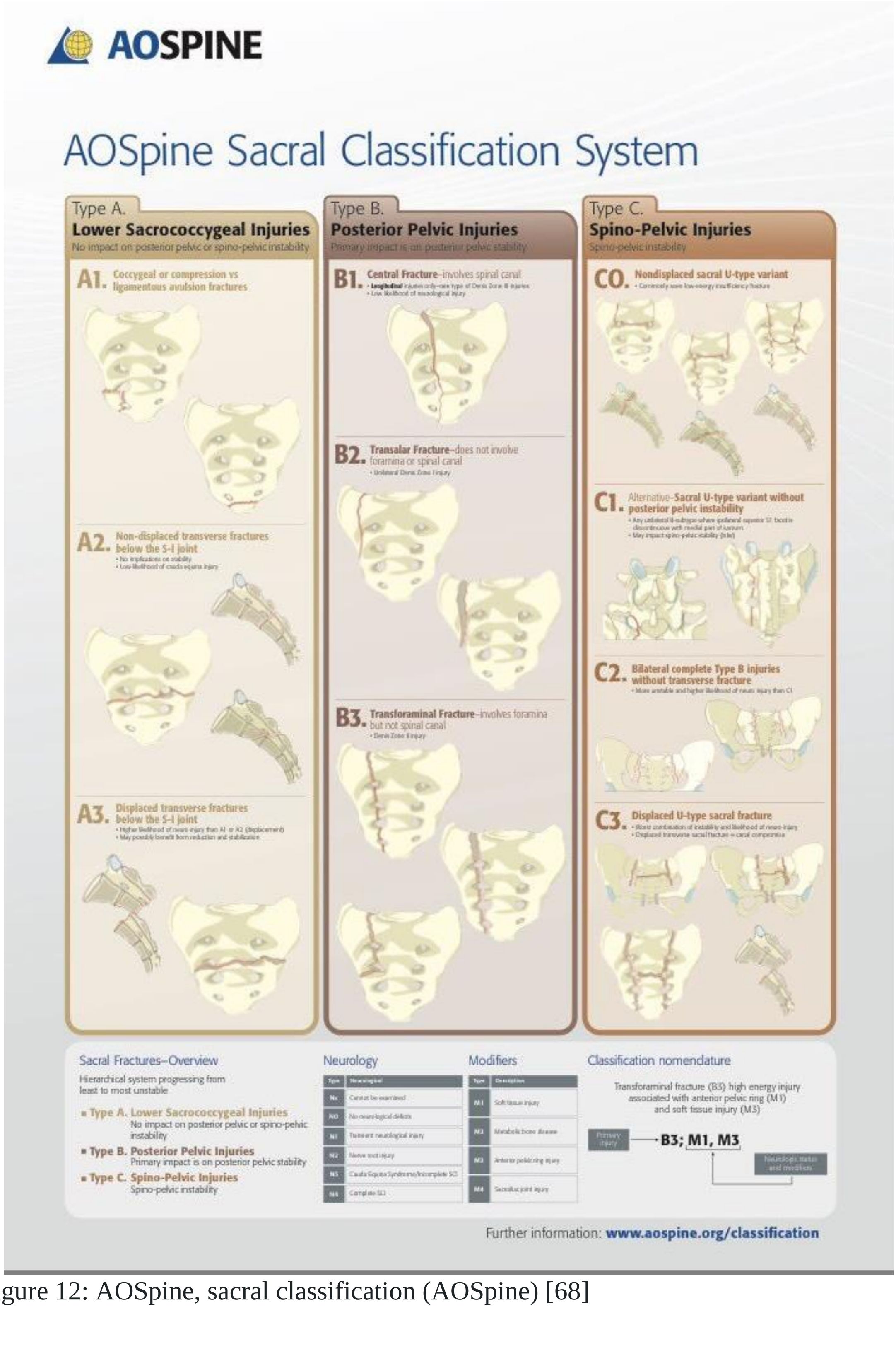


Figure 12: AOSpine, sacral classification (AOSpine) [68]

Besides the classification of the fracture pattern, the neurological impairment and the severity of injuries have to be classified. For neurological deficit the American Spinal Injury Association (ASIA) impairment scale is the most common one used (Figure 13).

Hereby, type A presents a complete impairment in the sacral segments S4-5 for sensory and motor function, B, C and D an incomplete impairment with persevered sensory respectively motor function with a muscle grad of less than 3 or above 3 (D), and finally E with normal motor and sensory function.

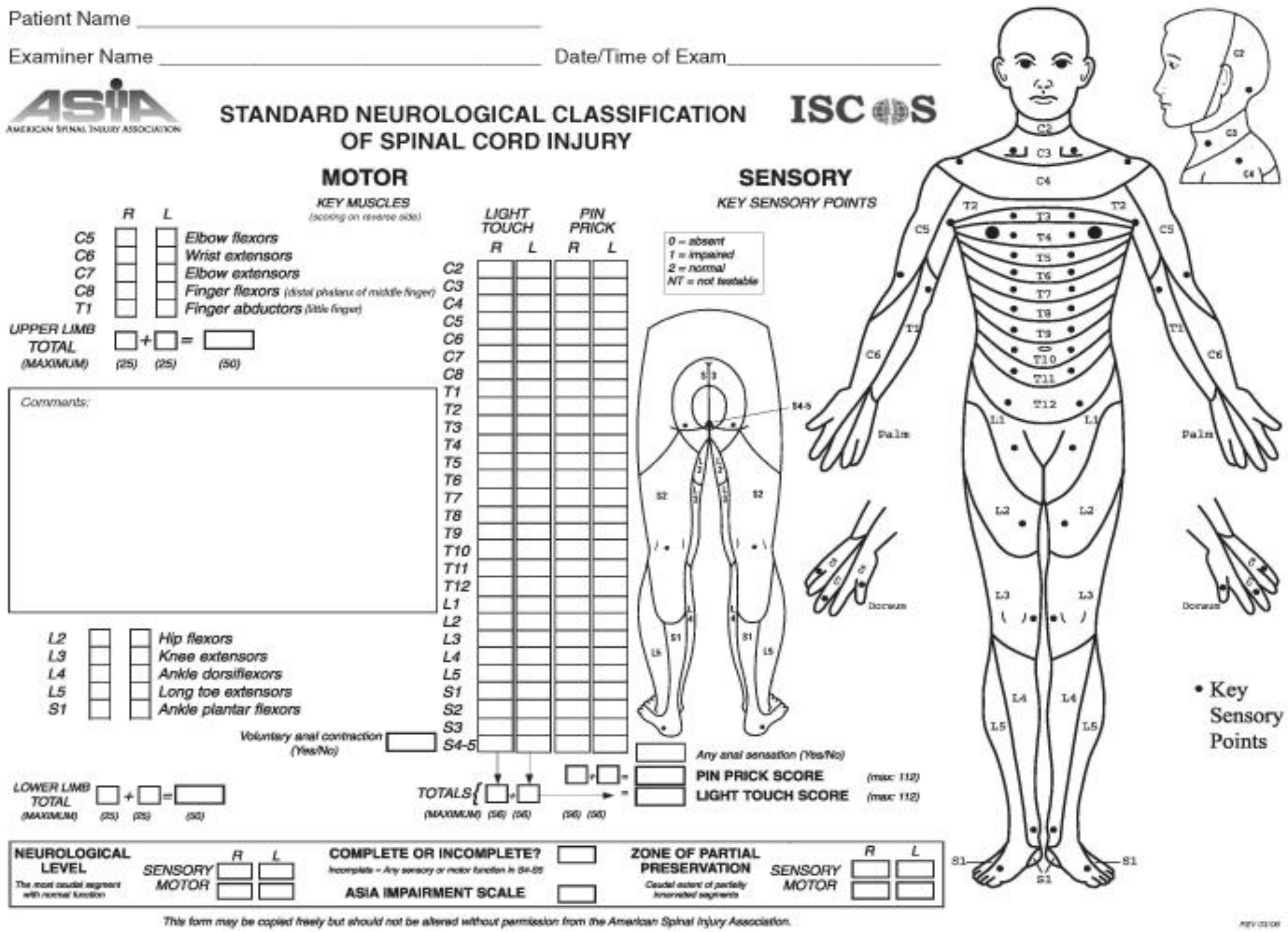


Figure 13: ASIA score [72], [73]

1.6 Treatment

In patients where spinal or sacral injuries are identified the further treatment must be planned. For spine fractures and spinopelvic dissociations this varies upon the stability including discoligamentous injuries, fracture pattern, presence of neurological impairment and other concomitant injuries. These range from conservative to operative procedures. Operative procedures include posterior percutaneous versus open stabilization and/ or decompression of the spinal canal, with or without anterior spondylodesis, stand-alone anterior spondylodesis for spine fractures.

For spinopelvic dissociation treatment varies upon the presence of concomitant injuries and the injury patterns. Since conservative treatment has been reported to lead to unsatisfactory results with persistent neurological deficit and permanent disability, [30], [74] surgical lumbopelvic stabilization after reduction of the sacral fractures and decompression of the neurological structures is the treatment of choice [75], [76]. Hereby, procedures include iliosacral screw stabilization and/ or triangular spinopelvic fixation for spinopelvic dissociation.

2. Objectives

Because of the dearth in literature on injuries such as sacral fractures including spinopelvic dissociation as well as spine fractures resulting from high traumatic energy accidents especially in airborne sports and subsequent treatment, we wanted to investigate the following based on five different publications.

1. Investigation of the logistics of patients' admission and primary examination in all patients suffering from aerial sport injuries.
    a. Admission of patients to the hospital which were divided into self-admission, by ambulance and air rescue.
    b. Initial diagnostics which was either performed in the emergency room or the resuscitation room.
2. Investigation of the incidence of spine injuries, demographic of patients and spinopelvic dissociation.
    a. Recording the patients' demographics such as age, gender and type of aerial sports.
    b. Assessment of the incidence of spine fractures and spinopelvic dissociations per all patients admitted to the hospital between the period of interest.
    c. Comparing the incidences of concomitant injuries including the evaluation of the proportion among patients suffering from spinopelvic dissociation and spine injuries.
3. Recording the different injury patterns and severity of injuries.
    a. Calculating the severity of injuries applying the ISS of the three most severe injured body areas and comparing between the different aerial sports and patient groups (i.e. spine patients, spinopelvic patients).
    b. Evaluation of the correlated onset of neurological impairment using the ASIA score.
4. The further procedure after completion of the diagnostics in the emergency room.

a. Assessment of the further surveillance either treatment as outpatient, general ward, intensive care unit or operating room among all patients.

b. If surgery for spine/ spinopelvic injuries was performed, the type of treatment differentiating between conservative, posterior percutaneous versus open stabilization and/or decompression of the spinal canal, with or without anterior spondylodesis, stand-alone anterior spondylodesis, iliosacral screw or triangular spinopelvic fixation.

5. The current knowledge on spinopelvic dissociation.

a. The demographics and different treatment options.

b. The establishment of a diagnostic and treatment algorithm.

6. Since MRI is not available in some cases and too time consuming especially in trauma patients the importance of DE-CT.

a. Assessment of the sensitivity and specificity of DE-CT of bone marrow and disc edema compared to conventional CT.

We hypothesize that patients who are admitted following airborne sports accidents are rather young, predominantly male with a high injury severity score. Further, because of the high energetic trauma, the spine and sacrum including the spinopelvic junction is predominantly affected. To optimize the diagnostic algorithm in trauma patients we hypothesize that Dual-Energy-Computed Tomography is a good alternative to MRI to detect discoligamentous injuries and we are able to developed a treatment algorithm for the treatment of spinopelvic dissociation.

3. Methods

At the university hospital Bern, Switzerland, which is a major level 1 trauma center we performed retrospective studies between February 2010 and June 2017. During this 7.5 year period we reviewed our emergency-care database at the hospital and included all patients who were older than 18 years at the date of hospital admission. Therefore, we obtained ethical consent from the Swiss ethical committee. Inclusion criteria consisted of patients who suffered from airborne sports related spine, sacral injuries or spinopelvic dissociation and were primarily admitted or transferred from another hospital to our emergency room. Aerial sports were defined as Paragliding, BASE-jumping, Speedflying, Delta flying and Parachuting. Primarily we focused on the different injury patterns among all patients and focused in a second step on patients with spine injuries and spinopelvic dissociations. Those patients who re-presented after primary examination and treatment or under the age of 18 were excluded from our study.

In all patients data on demographics, type of airborne sports, injury severity score, fracture pattern of spine injuries and sacral fractures including spinopelvic dissociation using the AO Spine classification respectively the Denis and Roy-Camille classifications were obtained. Furthermore, we assessed information about neurological impairment, concomitant injuries, indication and type of surgery as well as the acute trauma care management in the emergency department. To minimize the inter-observer bias of fracture classification, all radiographic images including LODOX, CT and if carried out the MRI scans were reviewed by one single orthopaedic surgeon (author of this thesis). In addition the injury severity score was calculated based on the information provided in the emergency database.

Following our studies we performed a systematic review on spinopelvic dissociation as well as on Dual-Energy-Computed Tomography, following the PRISMA guidelines. Therefore, the Medline, EMBASE, PubMed, Cochrane Library and Google database was searched. For search terms these included (spinopelvic dissociation) OR (spino-pelvic dissociation) OR (spondylopelvic dissociation) OR (lumbosacral dissociation), OR (lumbopelvic dissociation) OR (lumbo-pelvic dissociation) OR (U-shaped sacral) OR (suicidal fracture) OR (H-shaped sacral), respectively ((DECT) OR (DE-CT) OR (dual-energy CT) OR (Dual energy CT) OR (dual-energy computed tomography) OR (dual-energy-computed tomography) OR (dual energy computed tomography)) AND ((spine)

OR (vertebral)). Any duplicate results, lack of full access to original articles, review articles and editorials were excluded. All articles which presented findings on spinopelvic dissociation demographics, treatment procedures and clinical outcome (healing, complication rate) respectively Dual-Energy-Computed Tomography investigating the sensitivity, specificity and accuracy in English, German and French were included.

For statistical analysis, Microsoft Excel spreadsheet, Origin Pro 8.0 and IBM SPSS Statistics 25, using a descriptive statistic presenting demographics, injury pattern including neurological impairment was applied. The mean and standard deviation were used for normally distributed continuous variables. For further calculations and graphs we applied the multivariate ANOVA t-Test to analyse the level of significances between individual cohorts. Finally, to analyse any correlations and relationships between individual groups, i.e. aerial sports and spine injuries, respectively spinopelvic dissociation a linear regression model was applied.

For the meta-analysis on DE-CT the R software version 4.0.3 was used applying the mada^package. The true positive (TP), false positive (FP), true negative (TN) and false negative (TP) results were collected. To calculate the pooled sensitivity and specificity as well as PPV, NPV positive and negative likelihood ratio and diagnostic odds ratio a bivariate random-effect model was applied. In addition, the random-effects model, the method of moments (DerSimonian-Laird) was applied to calculate the τ^2 as well as I^2 to conclude on the heterogeneity. Considerable heterogeneity was defined between 70% and 100%. To analyse the correlation between sensitivity and specificity the Sherman's correction coefficient was calculated, where >0.6 was considered to be considerable.

The level of significances were set to * p-value≤ 0.05; ** p-value≤ 0.01 and *** p-value≤ 0.005.

4. Results

4.1 Overview of airborne injuries

During the period of interest, between February 2010 and June 2017, 237 patients were admitted to the university hospital Bern, Switzerland suffering from airborne injuries. Two patients had to be excluded since they were readmitted, leaving 235 patients for inclusion. The most common airborne sport performed was Paragliding (n=194/235; 82.6%; including 13 tandem-Paraglider) followed by BASE-jumping, Skydiving (one tandem-Skydiver), Speedflying and finally Delta flying. Male were predominant in 84.3% (n=198/235) and the mean age of patients was 38.7 years (Min/ Max 18 - 74). The mean injury severity score was 16.5 (SD 14, range from 0 to 75) which varied significantly upon the airborne sport performed. Highest ISS was observed in BASE-jumping however, without any significance (p=0.1). In total, 11 patients had to be intubated at the trauma site (4.7%; n=11/235). Most patients were admitted by air rescue in 66.0% (n=155/235) and 162 patients were primarily examined in the resuscitation room (n=162/235; 68.9%) or on the trauma normal ward (n=72/235, 30.6%). In one patient it was not mentioned in the medical reports were primary diagnostics were performed (n=1/235; 0.4%). Six patients were directly admitted by ambulance (n=6/235; 2.6%), whereas the remaining were either transferred from other hospital (n=44/235, 18.7%), self-admitted (n=28/235, 11.9%) or not otherwise specified (n=2/235, 0.9%).

After admission to the hospital, during examination in the resuscitation room three patients had to be resuscitated due to onset of a pulseless electrical activity of which two deceased unfortunately. One had a severe pelvis fracture, femoral fracture with liver laceration and hemopneumothorax, whereas the other patient suffered from a severe cranio-cerebral injury. In both cases only whole body low dose x-ray (LODOX) were performed without a computed tomography. The intrahospital mortality of patients suffering from airborne sports injuries was 0.9% (n=2/235) (per definition ISS 75). However, our database does not include the pre-hospital mortality. The demographics of patients and aerial sport distribution are illustrated in table 1.

	Overall	**Paragliding**	**BASE-jumping**	**Skydiving**	**Delta Flying**	**Speedflying**
Male (n (% of total numbers))	198/235 (84.3)	162/194 (83.5)	23/25 (92.0)	9/10 (90.0)	2/2 (100.0)	2/4 (50.0)
Injury Severity Score (n (SD))	16.5 (14.0)	16.0 (13.9)	21.1 (13.9)	13.3 (15.2)	18 (14)	19.8 (8.8)
Age (range)	38.7 (18-74)	39.8 (18-74)	30.8 (21-45)	37.2 (20-59)	51 (49-53)	33.3 (27-45)
Total Numbers (n (%))	235 (100.0)	194 (82.6)	25 (10.6)	10 (4.2)	2 (0.9)	4 (1.7)

Table 1: Swiss aerial sports patients' demographic [77]

4.1.1 Epidemiology of injuries

Within the 235 patients, 718 injuries were diagnosed which are 2.8 injuries per patient in mean. Most commonly, the spine was affected within 143 patients (n=143/235, or 60.9%) and 334 individual spine injuries (n=334/718, or 46.5%) as described in chapter 4.2, followed by thorax injuries (n=69/235, or 29.4%). Thorax injuries included lung laceration, lung contusion or edema (n=32/69, or 46.4%), followed by rib fractures (n=17/69, or 24.6%). Furthermore, fifteen subjects suffered from cardiac contusion, sternum fracture, or thoracic skin burning.

Abdominal injuries were less common in our cohort in 9.8% (n=23/235) and especially the liver was affected in 11 cases (n=11/235, 4.7%). Other injuries included the extremities with 122 (n=122/235, 51.9%) patients in total. Especially the lower extremity (n=65/235, or 27.7%) and the ankles were fractures (n=16/122, or 13.1%), followed by femoral fractures in 15 (12.3%, n=15/122) patients. Four patients (3.3%, n=4/235) suffered from combined fractures of the lower extremity. The upper extremity was affected in 24.3% (n=57/235).

The sacrum and pelvis injuries were observed in 52 cases of which most patients suffered from combined fractures (n=33/52, or 63.5%), followed by isolated sacral (n=11/52, or 21.2%) and pelvic fractures (n=8/52, or 15.4%) leaving 44 patients with sacral injuries. Finally, when looking at the face and head trauma we noted in 48 patients (n=48/235, or 20.4%) 52 injuries. The most common type of injuries were intracranial bleeds which occurred in 16 patients (n=16/48, or 33.3%), followed by concussions (n=15/48, or 31.3%). Skull fractures were present in nine patients (18.8%, n=9/48). All individual injuries are summarized in figure 14 and the distribution among the different airborne sports in table 2.

	Total	**Spine**	**Extremity**	**Sacro/ Pelvic**	**Abdomen**	**Thorax**	**Head/ Face**
Paragliding (%)	532/718 (74.1)	274/532 (51.5)	92/532 (17.3)	41/532 (7.7)	22/532 (4.1)	66/532 (12.4)	37/532 (7.0)
BASE-jumping (%)	134/718 (18.7)	48/134 (35.8)	33/134 (24.6)	12/134 (9.0)	5/134 (3.7)	26/134 (19.4)	10/134 (7.5)
Parachuting (%)	20/718 (2.8)	1/20 (5.0)	10/20 (50.0)	2/20 (10.0)	1/20 (5.0)	2/20 (10.0)	4/20 (20.0)
Speedflying (%)	24/718 (3.3)	11/24 (45.8)	2/24 (8.3)	-	1/24 (4.2)	9/24 (37.5)	1/24 (4.2)
Delta (%)	8/718 (1.1)	-	8/8 (100.0)	-	-	-	-
Total (%)	718 (100)	334/718 (46.5)	145/718 (20.2)	55/718 (7.7)	29/718 (4.0)	103/718 (14.4)	52/718 (7.2)

Table 2: Distribution of injuries according to the anatomic region in different airborne sports [78]

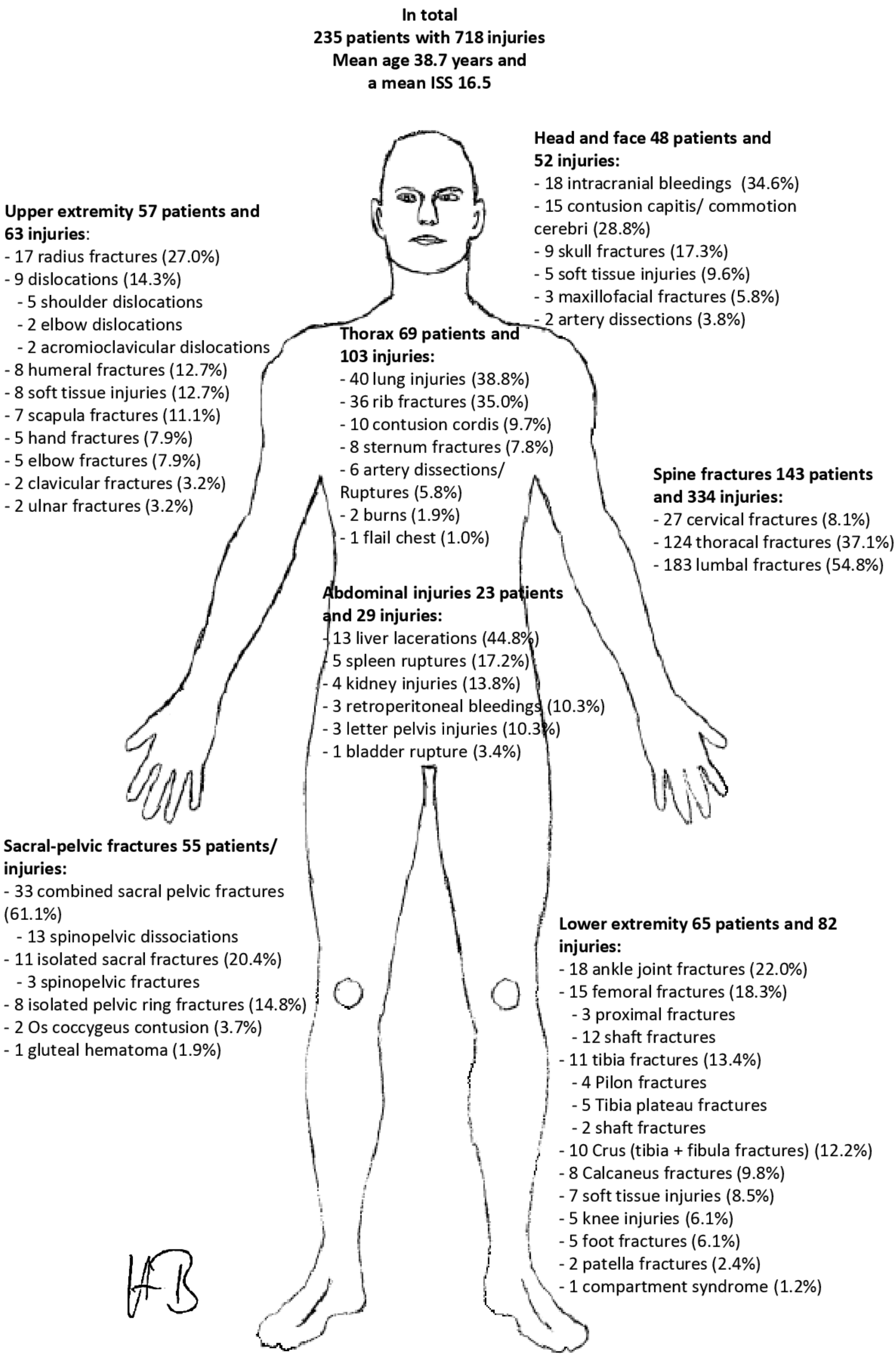


Figure 14: Distribution of all injuries [78]

4.1.2 Interventions and treatment

In the resuscitation room the implantation of 15 thoracic drainages and three invasive intracranial pressure (ICP) sensors were required. In 55 patients (n=55/235, or 23.4%) immediate emergency surgeries were indicated, whereas surgery was scheduled for another 61 patients within the following days (n=61/235, or 26.0%). For further surveillance, 19 patients were transferred to the intensive care unit (n=19/235, or 8.1%), in addition to the 55 patients who underwent emergency surgery (n=55/235, or 23.4%). Furthermore, 111 patients were hospitalized on the general ward (n=111/235, or 47.2%) and in total, 47 patients were treated as outpatient (n=47/235, or 20%) and were discharged from the emergency department within 24 hours. In terms of injury severity score, the ISS was significantly higher for the emergency surgery group (22.9) and the intensive care unit group (24.8) compared to all other patients (13.3; both $p<0.005$). All interventions and emergency surgeries are illustrated in table 3.

	Emergency surgeries	**Procedure**
Extremities (%)	18 (32.7)	10 external fixations, 4 plate osteosynthesis, 4 internal fixations with intramedullar nail
Open fractures	12	
Closed fractures	6	
Spine surgery (%)	23/55 (41.8)	16 decompressions and pedicle screw fixation, 7 percutaneous stabilizations
With neurology (%)	16/55 (69.6)	
Without neurology (%)	7/55 (30.4)	
Pelvic fixation (%)	7/55 (12.7), including one with urinary bladder rupture	7 plate osteosynthesis and in one case direct suturing of the bladder
Vascular surgery (%)	3/55 (5.5)	2 arterial bypasses, 1 coronary artery angiography
Others (Visceral, Plastic, Neuro, Maxillo Fascial)	4/55 (7.3%), each 1	1 explorative laparotomy, 1 debridement (after burn), 1 cerebral decompression, 1 maxillofacial fixation
Additionally interventions	15 thoracic trauma, 3 cerebral trauma	15 thoracic drainages, 3 ICP probe insertion
Total (%)	55 (100)	

Table 3: Emergency surgery indications including subsequent treatment classified by the leading medical specialty (ICP: Intracranial Pressure) [78]

4.2 Spinal fractures

When looking for patients suffering from spine injuries in total 148 were found (63.0%; n=148/235). No isolated discoligamentous injuries were observed. Most patients were primarily admitted to our hospital (n=129/148, or 87.2%) by helicopter (83.1% or n=123/148). Once the patient was transferred to our hospital initial diagnostics including primary and secondary survey was performed in the resuscitation room in 111 cases (n=111/148, 75.0%). At the trauma site, intubation was essential in five patients because of a Glasgow coma scale below or equal to 8.

The mean age was 39.4±12.3 years (range from 18 to 71) with predominately male patients (84.5%, or n=125/148). The ISS was slightly higher than the overall average with a mean of 17.9 (±13.2). Significantly higher scores were observed in BASE-jumping, Speedflying and Parachuting compared to Paragliding ($p \leq 0.01$). In 77 patients (52.0%, or n=77/148) more than one isolated vertebral body injury was observed resulting in 334 vertebral body fractures in total. In a further five patients spinal contusion (three lumbal and two cervical) were identified, resulting in 339 spinal injuries overall.

As mentioned before, since Paragliding it the most popular airborne sport, this accounted for the most injuries in 128 patients including 7 tandem flights, followed by BASE-jumping, Speedflying and two Parachuting (one tandem). Although injuries from Delta flying and other aviation sports were observed in our overall population, no spine injuries were found.

4.2.1 Classification

When looking for the most common affected vertebral body, L1 was injured in 20.1% (n=68/339), followed by L2 in 13.9% (n=47/339), T12 in 10.3% (n=35/339), and L3 in 8.8% (n=30/339). The distribution of the vertebral bodies is illustrated in figure 15.

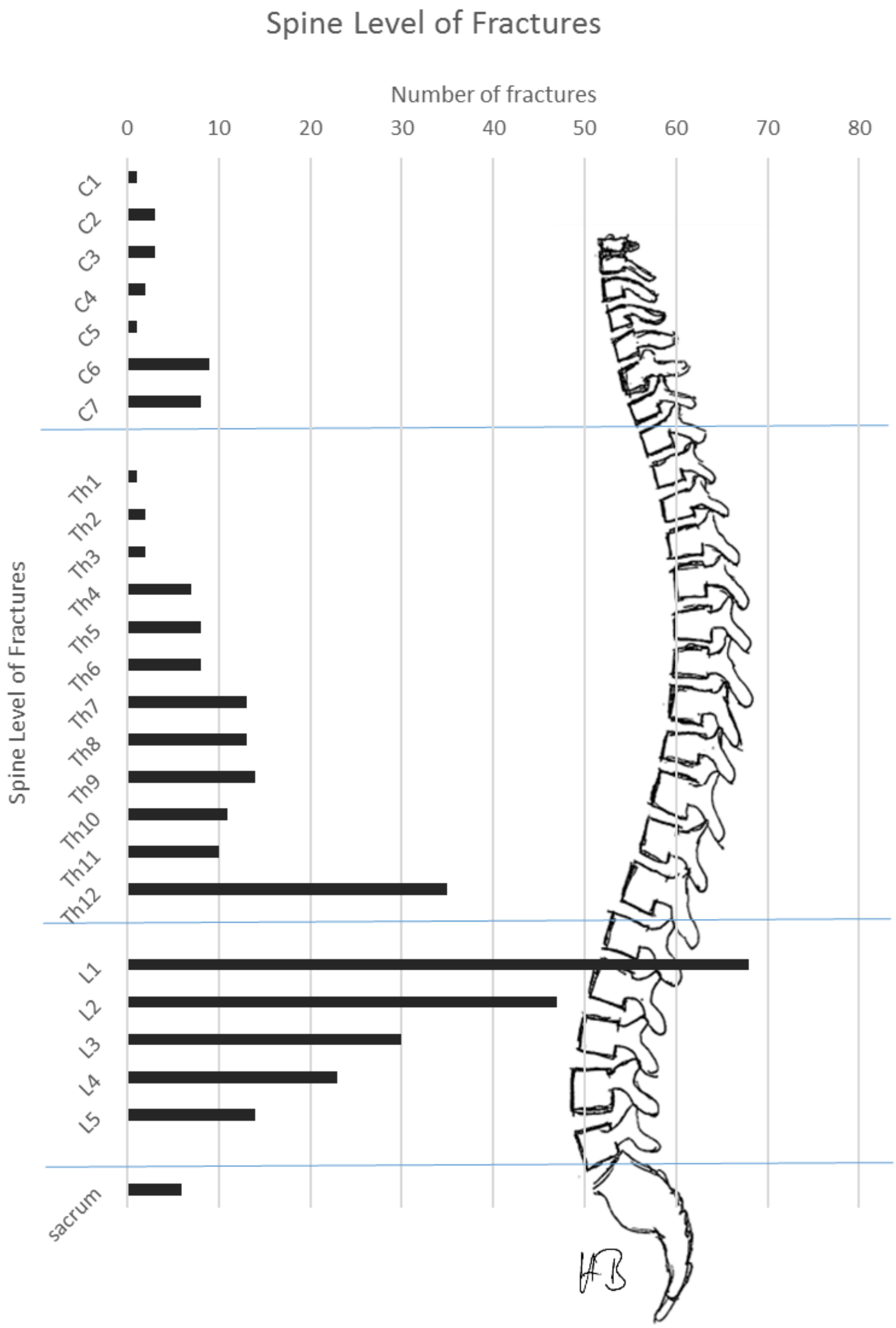


Figure 15: Distribution of spinal injuries [77]

In terms of severity, 272 spine fractures were classified as type A (n=272/334, 81.4%), followed by type B fractures in 13.8% (n=46/334), type C fractures in 1.8% (n=6/334), and in the remaining 10 patients the spinal facets were affected. In six cases (n=6/334, 1.8%) sacral injuries with a pelvic ring integrity were diagnosed. Of the 148 patients, traumatic dura tear was identified in 9.5% (n=14/148) and positive modifiers (M1 or M2) were found in 24 patients (n=24/148, 16.2%). Twenty-three of the 24 patients suffered from an indeterminate injury to the tension band on spinal imaging and one had ankylosing spondylitis. Figure 16 shows a patient suffering from a L3 C-type fracture before and after posterior stabilization and decompression.

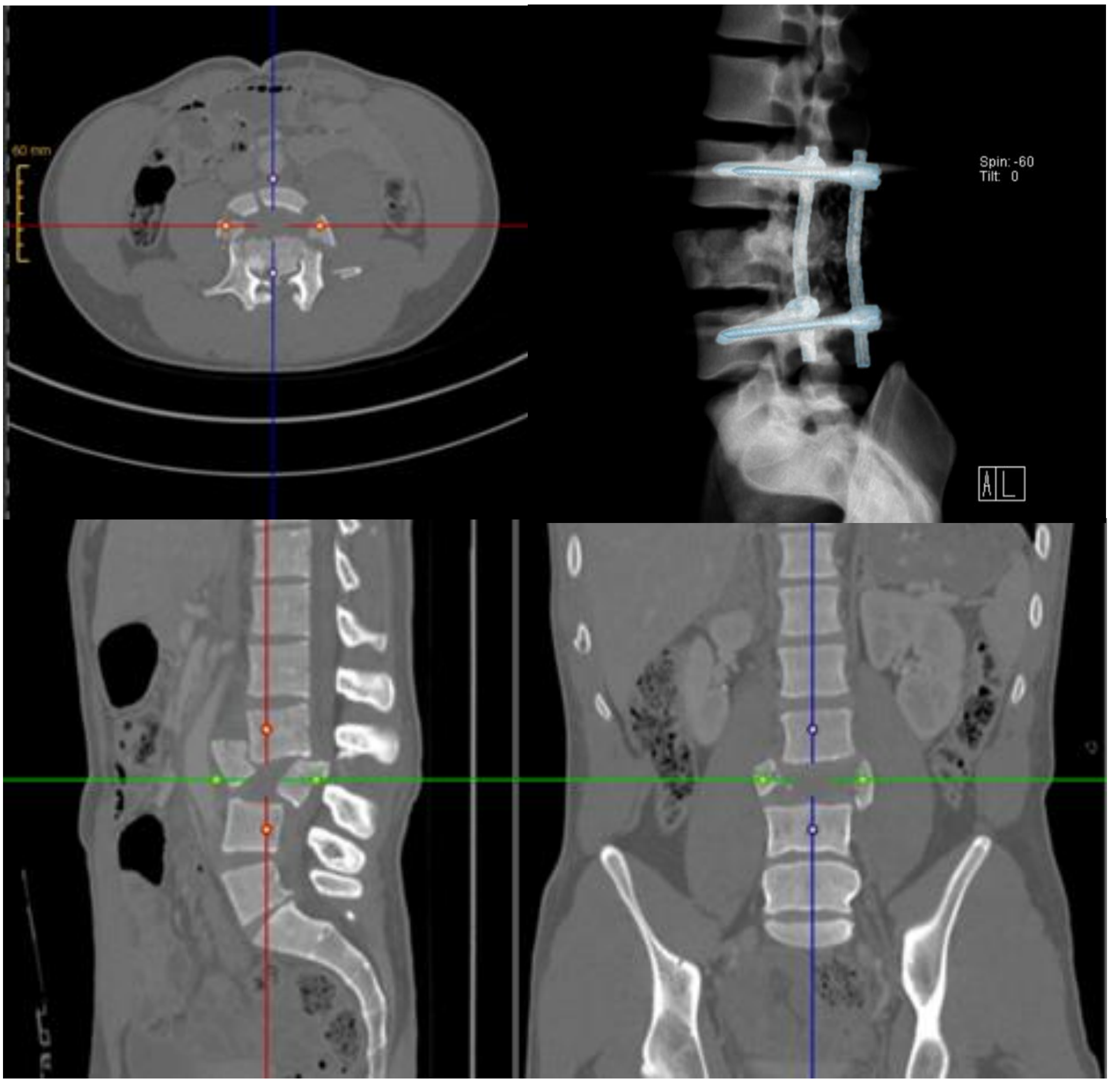


Figure 16: C-type L3 fracture before and after posterior stabilization and laminectomy

In terms of age, younger patients (<30 years of age) suffered primarily from thoracic and lumbar fractures, whereas patients between 30 and 50 years as well as above 60 years were rather diagnosed with fractures in the lumbar spine. The cervical fractures were predominant in 72% of cases in the age range between 40 and 60 years (n=18/25). When looking for the correlation between age and injury severity score, highest ISS with 27.6 was observed between 50 and 60 years of age (Table 4).

age range	Mean age	No of pat.	No. of injuries	ISS	cervical		thoracal		lumbal		sacral	
≤20	19.0	7	12	14.1	0	0	6	50.0	6	50.0	0	0
>20	26.4	33	88	19.1	2	2.3	41	46.6	43	48.9	2	2.3
>30	34.8	45	90	17.3	4	4.4	27	30.0	56	62.2	3	3.3
>40	46.6	33	77	16.1	10	13.0	22	28.6	44	57.1	1	1.3
>50	54.8	23	55	27.6	8	14.5	24	43.6	23	41.8	0	0
>60	65.1	7	17	18.2	3	17.6	4	23.5	10	58.8	0	0
Total		148	339	17.9	27	8.0	124	36.6	182	53.7	6	1.8

Table 4: The impact of patients’ age on injury severity score and location of injury in airborne sports related spine injuries [77]

When looking for neurological impairment, this was present in 20.9% (n=31/148) of all patients. According to the ASIA guidelines most suffered from type D (n=13/31, 41.9%), followed by type A in 25.8% (n=8/31), type C in 22.6% (n=7/31) and finally three type B ASIA scores (n=3/31, 9.7%). In another eight patients sensory deficit was observed which could not be classified according to the ASIA score. According to the detailed anamnesis no pre-traumatic neurologic deficits were present.

4.2.2 Surgery

Spinal surgery was indicated in 78 patients (n=78/148, 52.7%) due to instability or neurological impairment. Hereby, emergency surgery was performed in 23 patients (n=23/78, 29.5%) as a highly instable spine fracture (C-type fractures or highly comminuted A-type and B-type fractures with intraspinal bony fragments) (n=7/23, 30.4%) with onset of neurologic deficit or unclear neurologic exam in an intubated or unconscious patient (n=16/23, 69.6%) was diagnosed.

The most common procedure performed was the open posterior spondylodesis with 67.9% (n=53/78), followed by percutaneous posterior stabilization in 21.8% of cases (n=17/78), and eight stand-alone anterior spondylodesis with cage and plate (n=8/78, 10.3%). In addition to posterior stabilization anterior body replacement was performed in 50 cases (n=50/78, 64.1%). As traumatic dura tear was observed in 14 cases a running suture (n=13/14) or a fibrin patch was applied (n=1/14).

In another two patients surgery was indicated however, the patients wished to be operated at the hospital close to their hometown. Therefore the patients were transferred directly after initial diagnostics were performed and life-threatening diseases were excluded.

Postoperatively, improvement in neurological deficit was observed in seven patients, whereas it remained the same during the hospital stay in 24 patients. Two patients improved from ASIA type C (incomplete neurological deficit of muscle grade less than 3) to type D (incomplete motor function with muscle grade of 3 or more) and in another 5 patients ASIA score improvement from type D (slight neurological level of muscle grade 3 or more) to type E (normal function) was noted. In those who suffered from a complete neurological impairment no improvement was identified in the short-term, thus, sixteen patients were ASIA C or worse postoperatively.

4.2.3 Concomitant injuries

Besides the 334 spinal injuries in 148 patients, 95 patients (n=95/148, 64.2%) had 162 concomitant injuries including one severe burn and one patient who was successfully resuscitated after onset of a pulseless electric activity (PEA) after a BASE jump crash. All concomitant injuries are summarized in table 5.

	Overall	**Extremity**	**Pelvis**	**Abdomen**	**Thorax**	**Head/Face**
Paragliding (%)	128	39/48 (81.3)	19/26 (73.1)	9/14 (64.3)	38/47 (80.9)	21/27 (77.8)
BASE-jumping (%)	15	9/48 (18.8)	5/26 (19.2)	3/14 (21.4)	7/47 (14.9)	5/27 (18.5)
Parachuting (%)	2	-	1/26 (3.8)	1/14 (7.1)	-	-
Speedflying (%)	3	-	1/26 (3.8)	1/14 (7.1)	2/47 (4.3)	1/27 (16.7)
Total (% per overall)	148	48/148 (32.4)	26/148 (17.6)	14/148 (9.5)	47/148 (31.8)	27/148 (18.2)

Table 5: Concomitant injuries and type of hospital admission [77]

In addition to the 23 spine emergency surgeries, another 13 were indicated because of an unstable pelvic fracture in 5 cases, extremity fractures in another 5 patients – (4 femur fractures and one open ankle fracture, including two external fixations) and one exploratory laparoscopy (n=1). In the remaining two cases one skull fixation and one coronary angiography was performed (one for each; n=2).

In 12 patients a surveillance on the intensive care unit was required after initial assessment and 16 patients could be discharged from the emergency room the same day, as no severe injury was diagnosed. Those patients suffered from either contusion (n=5) or type A fractures (n=11). Prior discharge a standing X-ray was performed to exclude any further vertebral body compression and therefore instability.

4.3 Spinopelvic dissociations and sacral fractures

When looking for sacral fractures these were diagnosed in 44 patients (n=44/235, 18.7%). Likewise for spinal injuries, patients were primarily admitted to the hospital by helicopter in 79.5% (n=35/44) and examined in the resuscitation room in 81.8% of cases (n=36/44). Of the 44 patients most commonly sacral fractures without spinopelvic dissociation were observed (n=28/44, 63.6%). Spinopelvic dissociation were present in the remaining 16 cases (n=16/44, 36.4%). Likewise the overall demographics, there was a predominance in male with 72.7% (n=32/44). The mean age was 38.8 years old (SD 13.5) (Table 6).

Number of patients	**All injuries**	**All sacral fractures**	**Other sacral fractures**	**Spinopelvic dissociation**
All patients n (%)	235 (100.0)	44/235 (18.7)	28/235 (11.9)	16/235 (6.8)
Paragliding n (% per all patients)	194/235 (82.6)	34/44 (77.3)	21/28 (75.0)	13/16 (81.3)
BASE-jumping n (%)	25/235 (10.6)	8/44 (18.2)	6/28 (21.4)	2/16 (12.5)
Parachuting n (%)	10/235 (4.2)	2/44 (4.6)	1/28 (3.6)	1/16 (6.2)
Speedflying n (%)	4/235 (1.7)	-	-	-
Deltaflying n (%)	2/235 (0.9)	-	-	-
Age mean, (SD)	38.7 (12.3)	38.8 (13.5)	37.3 (12.4)	41.6 (14.9)
Gender (male (%))	194/235 (82.6)	32/44 (72.7)	21/28 (75.0)	15/16 (93.8)
Injury severity score, mean (SD)	16.5 (14.0)	26.8 (14.2)	20.4 (11.4)	38.1 (15.0)

Table 6: Proportion of sacral fractures and spinopelvic dissociation among airborne sports, percentages expressed in brackets [69]

4.3.1 Spinopelvic dissociations

The most common fracture patterns of spinopelvic dissociation were H-type in four cases, followed by three T-types (Figure 17), two U-types and two Lambda-types. No correlation to one of these patterns was observed in the remaining 5 cases. Especially the right side was affected in nine cases and five patients were injured at both sides. Only two patients suffered from a spinopelvic dissociation on the left side.

The most common complication reported was neurological impairment in four patients. Three of them suffered from an incomplete paraplegia or cauda equine syndrome (type B according to ASIA) and one patient was diagnosed with a traumatized lumbar plexus (type C according to ASIA).

Fourteen of sixteen patients underwent surgical stabilization and in the remaining two patients conservative treatment was recommended. One of the two patients had no concomitant injury or pelvic fracture, and the other one suffered from a non-displaced, stable spinopelvic dissociation. The most common procedure for fixation was percutaneous iliosacral screw stabilization in 43.8% (n=7/16) and in another 37.5% of cases a triangular stabilization (n=6/16) was performed either bilateral (n=4) or unilateral in two cases (n=2). In the remaining case a dorsal plate osteosynthesis for fixation was used. Retrospectively, we identified that the ISS was significantly higher in those patients who underwent triangular spinopelvic stabilization with a mean ISS of 46.3 (SD 14.7).

	Number of patients (n)	**Roy-Camille**					**Denis**				**AO**				**Fracture pattern**				
		Low TSF	0	1	2		1	2	3		A	B	C		T	λ	U	H	Neurology (ASIA score)
Spinopelvic dissociation	16	7	-	4	5		-	8	8		-	5	11		3	2	2	4	3B, 1C
Sacropelvic fractures	20	9	5	5	1		-	-	-		2	18	-		1	4	-	-	
Sacral fractures	8	3	2	1	2		4	-	-		6	2	-		1	-	-	-	

Table 7: Fracture pattern of spinopelvic dissociation [69]

	Conservative	Anterior fixation		Posterior fixation		Decompression
			Combined anterior/posterior fixation	SI-screw	Triangular fixation	
Spinopelvic dissociation	2	-	11	7	6	1
Sacropelvic fractures	12	3	1	4	-	-
Sacral fractures	8	-	-	-	-	-

SI= IlioSacral screw; TF= Triangular Fixation; For spinopelvic dissociation posterior fixation was performed in 13 cases, one decompression and two conservative treatments. Anterior fixation occurred performed in 11 cases where posterior fixation was performed.

Table 8: Treatment procedure in sacral fractures and spinopelvic dissociations [69]

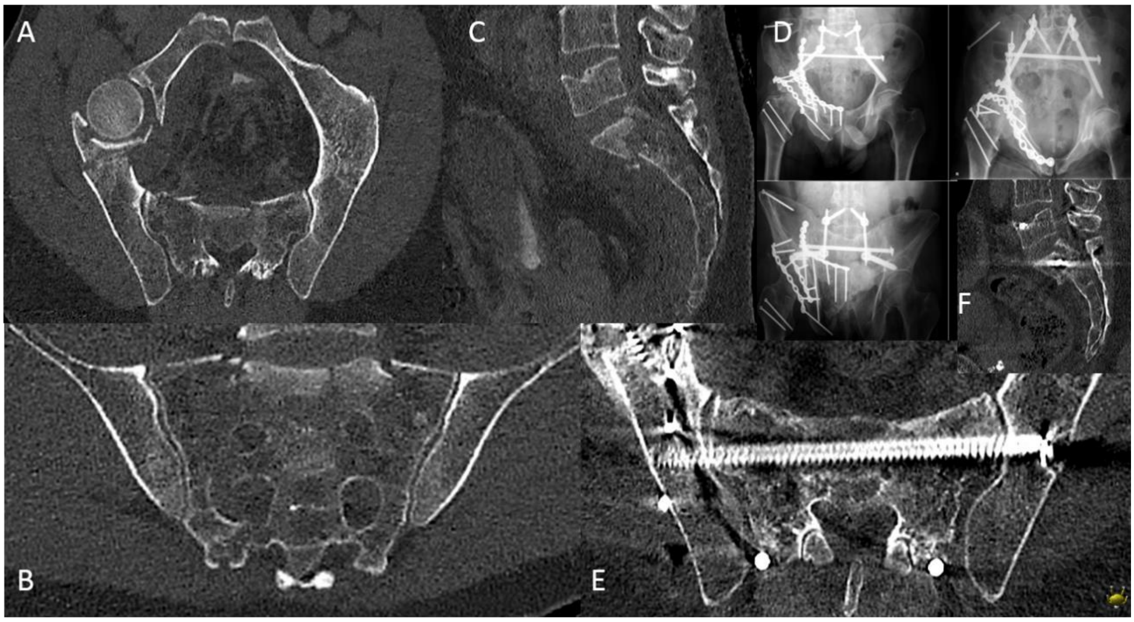


Figure 17: Patient suffering from a T-Type spinopelvic dissociation with comminuted acetabular fracture: A-C) fracture pattern, D) immediate postoperative X-ray, E-F) 1 year follow-up

4.3.2 Concomitant injuries

Concomitant spine injuries were identified in 12 patients (75.0%, n=12/16) and most commonly the lumbar one vertebral body was affected in 15.9% of cases. Besides spine fracture, thoracal injuries were found in 50.0% of cases (n=8/16) with three lacerations of the aortic arch and one traumatic dissection of the RIVA as well as intra-abdominal bleedings in 37.5% (n=6/16). Extremity traumas were less common of which the upper extremity was diagnosed in 31.3% (n=5/16), followed by the lower extremity in 25.0% (n=4/16) including one Morell-Lavallee lesion. Furthermore, three patients suffered from head and face injuries in 18.8% (n=3/16). All characteristics of the 16 patients are summarized in table 9.

Patient	Age	Gender	Type of airborne sport	ISS	Sacral fracture classification			Fracture pattern	Pelvic ring fracture (AO-classification)	Neurological deficit (AO-Spine classification)	Treatment[a]	Concomitant injuries[b]
					Denis	Roy-Camille	AOSpine					
1	59	M	Paragliding	45	3	2	C3	H-type	C1	-	4, 5	1, 2, 6
2	50	M	Paragliding	34	2	Low TSF	C1	T-type	C1	3	2, 5	1, 2, 4, 5
3	20	F	Parachuting	50	2	1	B4 right	L-type	C1	3	4	1, 6
4	37	M	Paragliding	35	2	Low TSF	C3	n.a.	C2	-	2, 4	1, 2, 5
5	50	M	Paragliding	50	3	2	C1	U-type	C2	-	2, 4	1, 5
6	30	M	BASE-jumping	26	2	1	C3	H-type	C1	-	2, 6	1
7	36	M	Paragliding	30	3	Low TSF	B4 left	L-type	C1	-	2, 4	1, 5
8	61	M	Paragliding	26	2	Low TSF	B4 right	n.a.	C1	-	2, 5	1
9	45	M	Paragliding	13	3	2	C1	T-type		-	1	1
10	38	M	Paragliding	34	3	2	C1	H-type		-	1	1, 3, 5
11	27	M	BASE-jumping	66	3	Low TSF	B4 left	n.a.	C1	3	2, 3, 5	1, 3, 4, 5, 6

12	71	M	Paragliding	50	2	Low TSF	C2	T-type	C2	2	2, 4	1, 3
13	43	M	Paragliding	50	3	1	C3	H-type	C2	-	2, 4, 5	2, 6
14	19	M	Paragliding	57	2	2	C3	U-type		-	5	2, 3, 4, 5, 6
15	29	M	Paragliding	18	3	Low TSF	C1	n.a.	C1	-	2, 4	5, 6
16	50	M	Paragliding	25	2	1	B4 right	n.a.	C2	-	2, 4	-

ISS = mean injury severity score; TSF = transverse sacral fracture; [a] treatment: 1 conservatively, 2 osteosynthesis of the anterior pelvic ring, 3 decompression, 4 iliosacral screw, 5 triangular lumbopelvic osteosynthesis; [b] concomitant injuries: 1 spine, 2 upper extremity, 3 lower extremity, 4 head and face, 5 thoracic trauma, 6 intra-abdominal trauma

Table 9: Characteristics of 16 patients with spinopelvic dissociation [69]

4.3.3 Sacral fractures

Other sacral fractures were identified in 28 cases of which sacropelvic fractures were diagnosed in 20 patients and isolated sacral fractures in 8 patients. Most commonly these were of low trans-sacral fractures. According to the AO-classification most sacropelvic fractures were type B (n=18/20) respectively in isolated sacral fractures (n=2/20), followed by type A fractures in 2 of 20 cases for sacropelvic fractures and 6 for isolated sacral fractures. For fracture pattern, Lambda-type was observed in 4 patients for sacropelvic dissociation (n=4/20) respectively T-type one each for sacropelvic and isolated sacral factures (n=1/20; n=1/8).

A majority of those patients underwent conservative treatment in 71.4% (n=20/28). In the remaining eight patients either single anterior pelvic fixation was performed (n=3/28, 10.7%) or iliosacral screw fixation (n=5/28, 17.9%) and one combined anteroposterior stabilization. Luckily, no neurological impairment was observed. Likewise, for spinopelvic dissociation, the most common concomitant injuries were spine fractures in 17 patients (n=17/28, 60.7%). Others included pelvic ring injuries (n=19/28), extremity fractures (n=16/28) and thoracic injuries (n=9/28) as illustrated in table 10.

4.3.4 Comparison between spinopelvic dissociations and other sacral injuries

Although demographics including age and gender were equally distributed, the injury severity score for spinopelvic dissociation was significantly higher with 38.1 compared to 20.0 (standardized coefficient of 0.463, p=0.001). Other than that, spinopelvic dissociations were more commonly associated with vertebral body fractures with 75.0% in the spinopelvic dissociation group and 60.7% in the other sacral fracture group (standardized coefficient of 0.329, p=0.03). In addition, the incidence of neurological impairment was 25.0% in the spinopelvic dissociation group versus 0.0% in the other sacral fracture group. Other than that no significances were found for other concomitant fractures.

	ISS	**Number**	**Spine**	**Extremity**	**Pelvis**	**Abdomen**	**Thorax**	**Head/ Face**
Spinopelvic dissociation (%)	38.1	16	12/16 (75.0)	11/16 (68.8)	14/16 (87.5)	6/16 (37.5)	8/16 (50.0)	3/16 (18.8)
Other Sacral fractures (%)	20.0	28	17/28 (60.7)	16/28 (57.1)	19/28 (67.9)	4/28 (14.3)	9/28 (32.1)	3/28 (10.7)
Total (%)	26.8	44	29/44 (65.9)	27/44 (61.4)	33/44 (75.0)	10/44 (22.7)	17/44 (38.6)	6/44 (13.6)

ISS= Injury Severity Score

Table 10: Concomitant injuries related to spinopelvic dissociation and sacral fractures [69]

4.4 Systematic Review on Spinopelvic dissociation

As outlined in our studies, spinopelvic dissociation is a rare injury with an incidence of 6.8% (n=16/235) among airborne sports between February 2010 and June 2017. Until today no gold standard for fixation exists, why we were interested in the current literature and establishing an algorithm for treatment.

In total, 216 studies were found including 75 duplicates. Ninety-one studies did not meet inclusion criteria, leaving 50 articles to be included for the systematic review and meta-analysis between 1969 and 2018 according to PRISMA Guidelines (Figure 18).

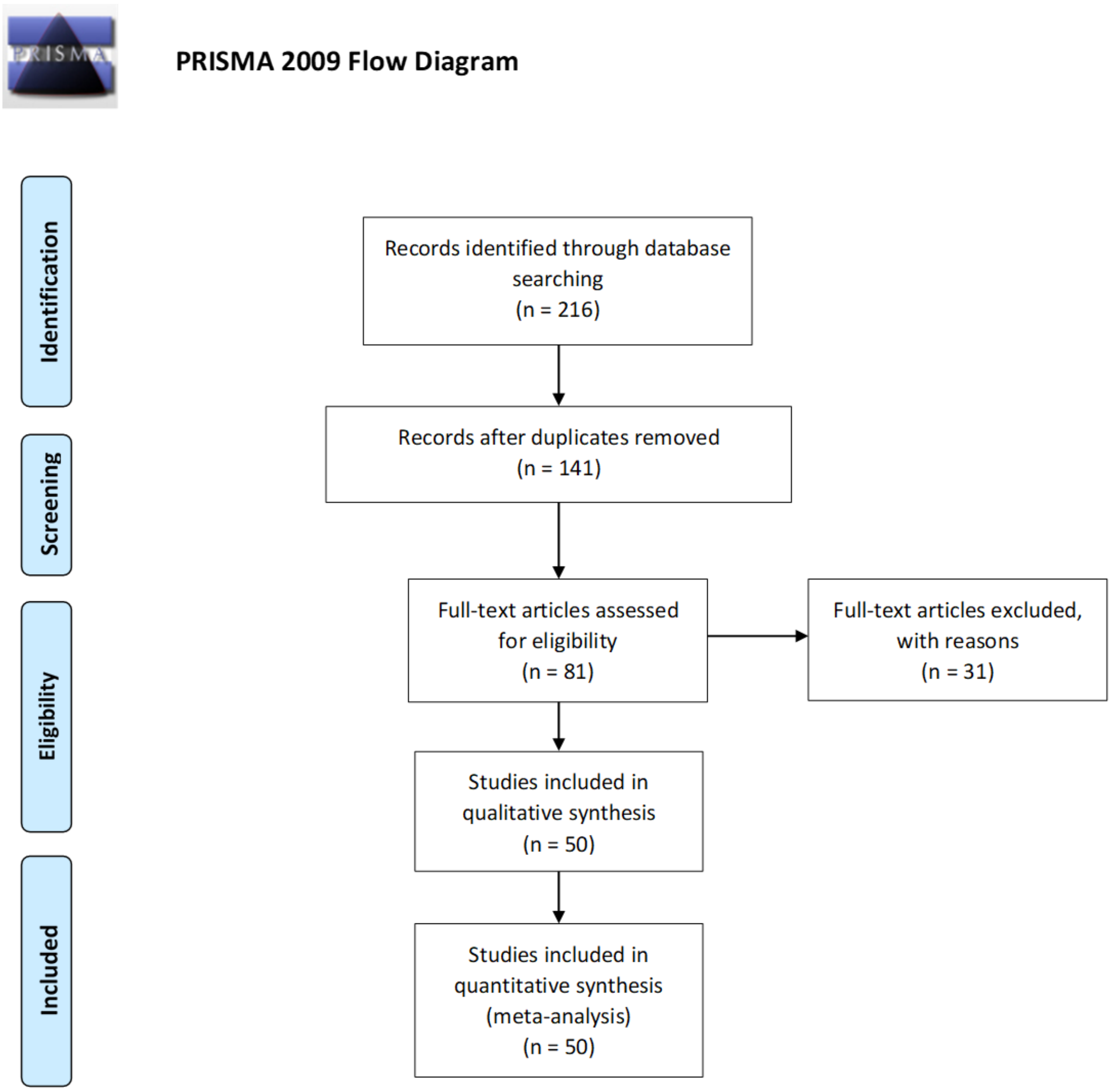


Figure 18: PRISMA Flow diagram of inclusion criteria for spinopelvic dissociation [70]

4.4.1 Demographics of included studies in the systematic review

The 50 studies, reported 379 spinopelvic dissociations between 1969 and 2018 which outlines the rarity of this injury. The mean age of patients was even younger with 31.6 ± 11.6 years compared to our study. Furthermore, the gender was equally distributed with 49.3% being male (n=187/379). In 309 subjects the cause of injury was mentioned which in most cases was fall from a height like airborne injury (n=172/309, 55.7%). Of the 172 cases, 64 were suicide attempts (n=64/172, 37.2%) and in the remaining 108 cases other causes such as airborne sports injuries were reported. The second largest group was road traffic accidents (n=88/309, 28.5%) which included 72 cases of motor vehicle accidents as well as 16 bicycle and pedestrian accidents. In the remaining cases blast injuries (n=22/309, 7.1%) or other causes (n=27/309, 8.7%) were reported (spinal tuberculosis, epileptic seizure, osteoporotic, assault, shotgun injuries, helicopter accident or crush injury). Additionally, eight studies reported the injury severity score at a mean of 23±3.8.

4.4.2 Treatment and neurological impairment

In the majority of cases surgical fixation was performed (93.1%, n=353/379). The mean time from injury to surgery was 8.6±9.9 days (range from 0 to 43.5 days) [79], [80]. In the remaining 26 patients conservative treatment was initiated. For neurological impairment, 258 patients suffered from deficits before surgery (73.1%, or 258/353). Postoperatively, an improvement was observed in 168 patients (65.1%, 168/258), although 137 patients still had some degree of neurological impairment (53.1%, n=137/258). In 90 patients a remaining cauda equine syndrome (34.9%, n=90/258) after surgery was noted. Hereby, it has to be mentioned that only single case reports observed no neurological impairment, whereas in case series this was lowest with 19.4% of patients (n=6/31) suffering from neurologic impairment [81]. Some other authors reported an incidence in neurological impairment in up to 100% of cases [27], [82]. All demographics, etiologies, injury severity score, neurological impairment before and after surgery as well as type of surgery are summarized in table 11.

	Total	No of studies	Literature
Number of patients	379	50	[26, 27, 29, 30, 44, 51, 74, 75, 79-81, 83-121]
Gender male (%)	187 (49.3)	46	[26, 29, 30, 44, 51, 74, 75, 79-81, 83-86, 88-95, 97-120]
Age	31.6±11.6	46	[26, 29, 30, 44, 51, 74, 75, 79-81, 83-95, 97-111, 113-120]
Trauma mechanism (%)	309 (100.0)		
Fall from heights (%)	172/309 (55.7)	32	[27, 44, 51, 74, 75, 79, 80, 83, 85-88, 91, 92, 94, 95, 97-99, 102-104, 106-109, 112-116, 120]
Road accidents (%)	88/309 (28.5)	28	[26, 27, 29, 30, 44, 74, 75, 83-85, 90, 91, 94, 95, 98, 101, 102, 104, 105, 107, 109, 111, 112, 115-117, 119]
Blast Injuries (%)	22/309 (7.1)	5	[30, 89, 93, 96, 100]
Others (%)	27/309 (8.7)	13	[30, 44, 74, 87, 91, 95, 99, 102, 107, 110, 111, 116, 118]
ISS	23.1±3.8	8	[44, 51, 74, 83, 91, 92, 102, 106]
Neurological deficit before (%)	258/353 (73.1)	49	[26, 27, 29, 30, 44, 51, 74, 75, 79-81, 83-90, 92-121]
Neurological deficit post treatment (%)	137/258 (53.1)	40	[26, 29, 30, 44, 51, 74, 75, 79, 80, 83-85, 87, 90, 93-108, 111-115, 117-121]
Cauda equine syndrome (%)	90/258 (34.9)	32	[26, 29, 30, 44, 74, 75, 79, 80, 83-85, 87, 90, 93, 98, 99, 104, 106-108, 111, 113-115, 117-121]

Neurological improvement (%)	168/258 (65.1)	31	[27, 30, 44, 51, 74, 75, 80, 83-87, 90, 92-99, 102, 105, 107, 108, 111-113, 115, 119-121]
Surgery (%)	353/379 (93.1)	49	[27, 29, 30, 44, 51, 74, 75, 79-81, 83-121]
Conservative (%)	26/379 (6.9)	8	[26, 27, 80, 83, 94, 96, 99, 109]

Table 11: Overview of demographics, causes of injury, concomitant neurological impairment, treatment procedures based on the systematic review [70]

4.4.3 Surgical fixation techniques

Within the 353 patients where a surgery was performed, 216 patients underwent open reduction (61.2%, n=216/353), and in 95 patients a closed reduction was performed (26.9%, n=95/353). In the remaining 42 cases (11.9%, or n=42/353) no reduction was performed [93] or not further specified [86], [51], [96], [100], [103], [80], [116]. Additionally, in 168 patients (47.6%, n=168/353) a decompression and/ or laminectomy was performed, whereas in 24 cases (6.8%, n=24/353) no decompression was performed. In the remaining 161 cases it was not otherwise specified. In four cases only an open reduction (n=1) or sacral laminectomy (n=3) [99], [80] was performed without fracture fixation.

For posterior fixation, most commonly, triangular fixation (TF) was performed in 243 cases (68.8%, n=243/353) and especially without iliosacral screw (SI) fixation (n=179, 50.7%). 26 patients underwent a combined triangular fixation with iliosacral screw fixation (n=26/353, 7.4%). In 38 cases (10.8%, n=38/353), a posterior lumbopelvic fixation was performed but without further specification if a combination with an SI screw or not was performed. A single iliosacral screw was performed in 75 patients (21.2%, n=75/353). Other fixation methods included plate osteosynthesis in 8 cases (2.3%, n=8/353) and in the remaining 6 studies ventro-dorsal stabilization [30], triangular fixation with plate osteosynthesis [102], treatment with external fixator alone or in combination with triangular fixation [108], block resection (n=4) [27], combined triangular posterior fusion with cage implantation [84], combined iliosacral screw fixation with plate osteosynthesis [115] or long sacral harrington hook modified for square stabilization was performed [27], [90]. Irrespective of the surgical technique, the healing rate was 100% in 307 patients, whereas in the remaining 46 patients (13.0%, 4 studies) no statement about fracture healing was made.

For follow up this was 23.6 months (range 3 months to 132 months) in mean. Five studies did not mention the follow up period [101], [109], [110], [111], [27] and in two no complications were reported [27], [112]. 96 of 321 patients (29.9%) had complications which ranged from superficial infection, screw disengagement, facet arthropathy to osteomyelitis. The highest complication rate was >100%, as one study noted 35 complications in 28 patients [85]. All surgical techniques, follow up, healing rate and complications are summarized in table 12.

	Total	No of studies	Literature
Surgery (%)	353 (100.0)	49	[27, 29, 30, 44, 51, 74, 75, 79-81, 83-121]
TF without SI screw (%)	179/353 (50.7)	25	[29, 51, 74, 75, 79, 81, 83, 85, 87-89, 92, 96, 98, 100, 102, 107, 108, 110, 114, 116-121]
TF with SI screw (%)	26/353 (7.4)	5	[75, 87, 92, 98, 102]
PSF NOS (%)	38/353 (10.8)	4	[30, 94, 95, 97]
SI screw fixation (%)	75/353 (21.2)	18	[30, 44, 51, 87, 89, 91, 92, 96, 98, 101, 103-106, 109, 111, 112, 115]
Plate osteosynthesis (%)	8/353 (2.3)	5	[27, 86, 92, 96, 113]
others (%)	6/353 (1.7)	7	[27, 30, 84, 90, 102, 108, 115]
Open reduction (%)	216/353 (61.2)	28	[27, 29, 30, 74, 75, 81, 83-85, 90, 92, 94, 95, 97-99, 102, 105, 107, 109-113, 115, 117-120]
Decompression/ Laminectomy (%)	168/353 (47.6)	45	[27, 29, 30, 44, 51, 74, 75, 79-81, 83-90, 92-99, 101-104, 107-116, 118-121]
Surgery delay (days)	8.6±9.9	34	[29, 30, 44, 74, 75, 79, 80, 84, 86-90, 92, 95, 97-108, 110, 111, 113, 114, 116-118, 120]
Follow-up (months)	23.6±25.2	46	[26, 29, 30, 44, 51, 74, 75, 79-81, 83-100, 102-108, 112-121]
Healing rate (%)	307/307 (100.0)	46	[26, 29, 30, 44, 51, 74, 75, 79, 80, 83-108, 111-121]
Complications (%)	96/321 (29.9)	46	[26, 29, 30, 44, 51, 74, 75, 79-81, 84-111, 113, 114, 116, 117, 119-121]

Table 12: Surgical procedures, follow-up time and associated complications; SI – IlioScaral screw; TF – Triangular Fixation; PSF – Posterior Spinal Fusion; NOS – Not Otherwise Specified [70]

4.5 Meta-Analysis on Dual-Energy-Computed Tomography

Within our systematic review 13 studies (Figure 19) presenting data on the sensitivity, specificity and accuracy of DE-CT of bone marrow and disc edema in spine injuries with a total of 515 patients analyzing 3,335 vertebrae and 929 fractures (27.8%) were found.

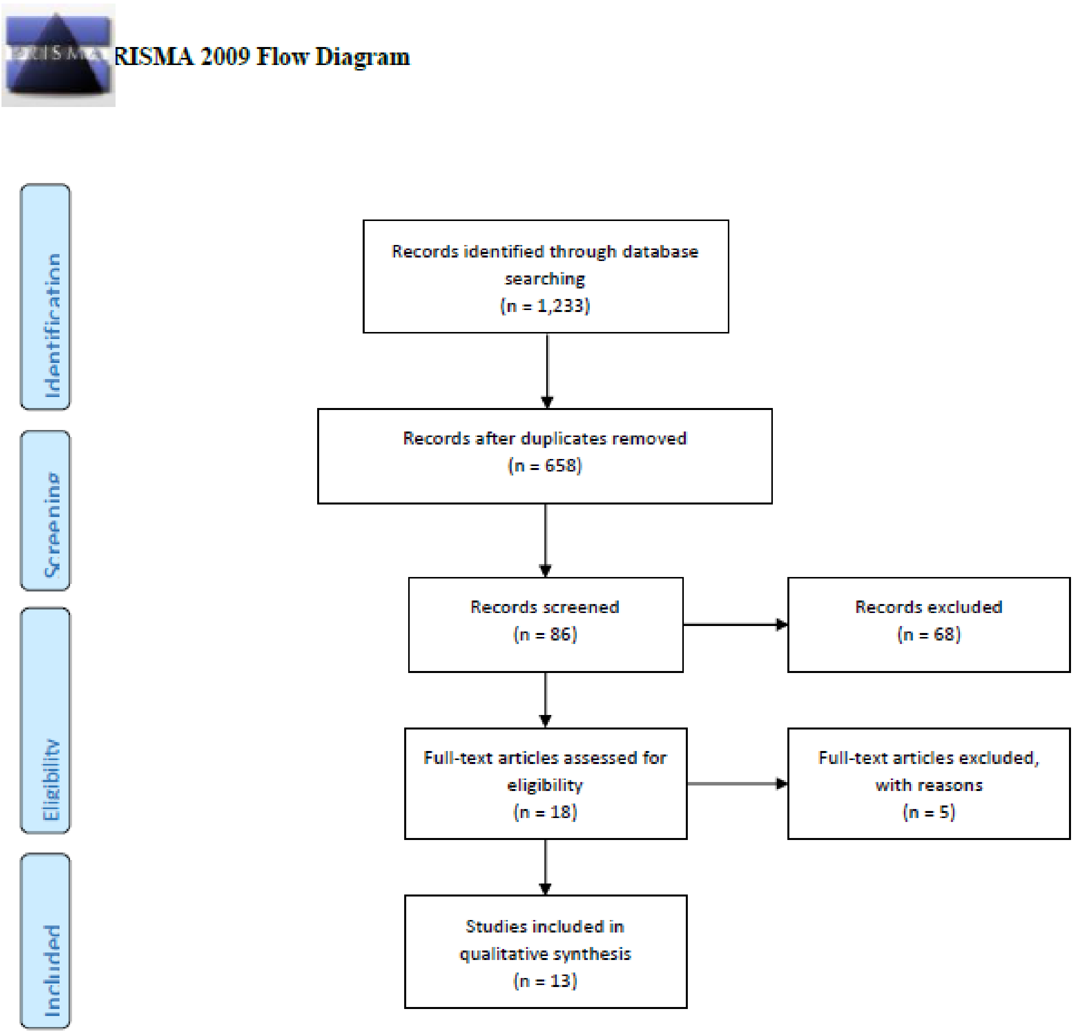


Figure 19: Included articles according to the PRISMA Guidelines for DE-CT [122]

The majority of studies were of a prospective blinded (n=9/13) and 4 of retrospective design. Hereby, most of the studies assessed the individual vertebrae [123], [124, 125] and the primary end point included bone edema [126] respectively comparisons between DE-CT and conventional CT (n=6/13). All individual studies are listed in table 13.

Studies	Year	QoE	Number	Female	Age	Vertebrae	Fract./ D/BME	Design	MRI	experience
Kaup M	2016	III	49	21	69.2	528	144	retrospective, blinded	1.5 Tesla TIRM	Radiologist between 13-25y
Pumberger M	2019	II	67	NM	70.7	295	142	prospective	1.5 Tesla STIR	Radiologist 8y, Trauma surgeon 8y, Student 1y
Neuhaus V	2018	III	34	8	NM	383	57	retrospective, blinded	3 Tesla STIR	NM
Diekhoff T 2019	2019	II	70	23	70.7	548	192	prospective, blinded	1.5 Tesla STIR	Radiologist 8y, Trauma surgeon 5y, Student 1y
Karaca L	2016	II	23	5	61	209	47	prospective, blinded	3 Tesla STIR	Radiologist 20y and 15y
Bierry G	2014	II	20	4	69	185	16	prospective, randomized, blinded	1.5 Tesla STIR	Radiologist 30y and 6y
Diekhoff T 2017	2017	IV	9	3	75	23	14	prospective, blinded	1.5 Tesla STIR	Radiologist 6y and 15y, Trauma surgeon 3y
Schwaiger BJ	2018	III	27	10	72	59	41	retrospective, blinded	3 Tesla STIR	Radiologist both 6y

Foti G	2019	II	76	29	62.3	774	113	prospective, multi-institutional, blinded	1.5 Tesla TIRM	Radiologist 35y, 15y
Petritsch B	2017	II	22	9	60	163	37	prospective, blinded	3 Tesla TIRM	Radiologist 8y, 3y, 11y
Wang CK	2013	II	63	NM	71.6	112	112	prospective blinded	1.5 Tesla	2 Radiologist
Na D	2016	III	38	25	55.6	NM	24	not mentioned	NM	
Engelhard N	2019	III	17	NM	70	56	24	prospective blinded	1.5 Tesla STIR	Radiologist 8y, 2y, Student 1y
Total			515	61.4	65.6± 5.95	3,335	926 (27.8%)			

Table 13: Demographics of included studies; QoE – Quality of Evidence; D/BME – Disc/ Bone Marrow Edema [122]

Other focuses of interest included difference cut-offs for Hounsfield unit of 50 HU or reconstruction algorithm such as material decomposition and calcium substraction [127], [128]. For comparisons the majority of authors used a 1.5 Tesla [129], [127], [123], [124, 125], [130], [128], [131], short tau inversion recovery (STIR) [126], [129], [123], [124, 125], [132], [133], [128] or turbo inversion-recovery magnitude (TIRM) sequences [127], [130], [134]. Figure 20 illustrates the difference between a DE-CT and normal CT.

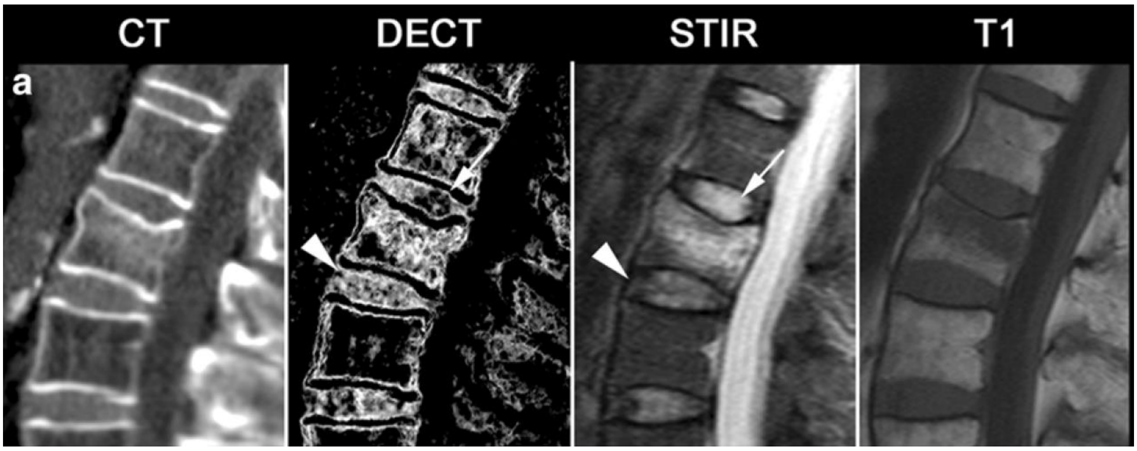


Figure 20: Patient with a compression fracture with bone marrow edema at L2 and an increased singal intensity in the disc L1/2 based on MRI-STIR. Image from publication by Pumberger M et al [123]

4.5.1 Sensitivity, specificity and accuracy of DE-CT compared to CT

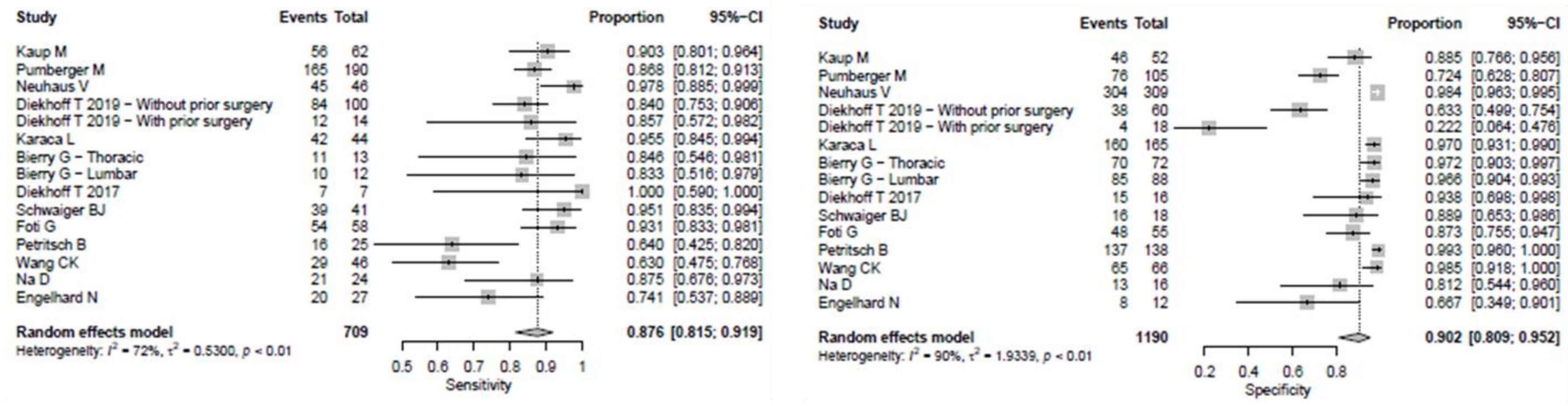
The mean age of patients was 67.6± 5.95 years and females were primarily included in 61.4% (n=205/334) of cases. The largest cohort included 76 patients with 774 vertebrae [124, 127]. For overall sensitivity and specificity this was described with 86.2% respectively 91.2% with a PPV of 85.3% and NPV of 91.7%. The overall accuracy was 89.3% and the heterogeneity was found be considerable (I^2>70%) in all cases (Table 14; Figure 20).

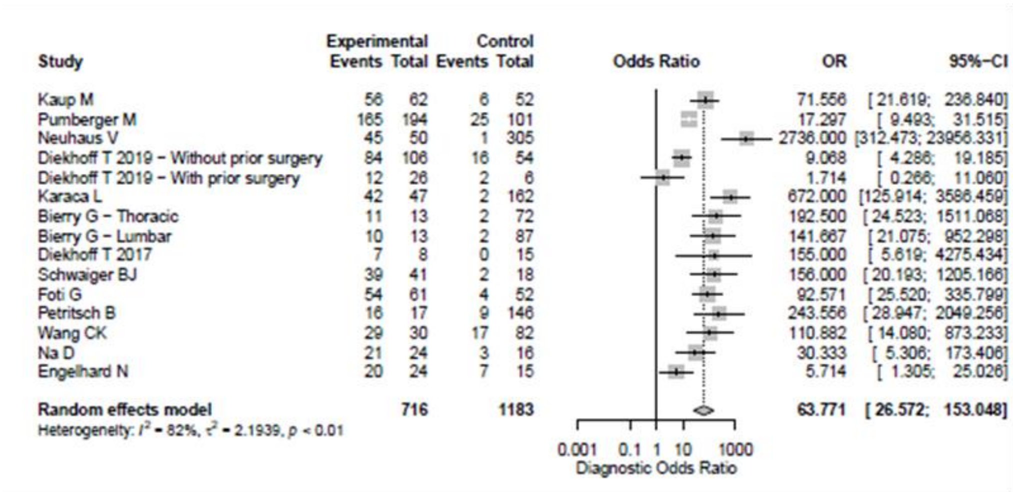
Studies	Sen	95% CI	Spec	95% CI	PPV	95% CI	NPV	95% CI	Acc.	95% CI	Incon.
Kaup M	90.3	80.1-96.4	88.5	76.6-95.7	90.3	81.4-95.2	88.5	78.1-94.3	89.5	82.3-94.4	
Reader 1	82.3	70.5-90.8	84.6	71.9-93.1	86.4	76.9-92.4	80.0	69.8-87.4	83.3	75.2-89.7	7
Reader 2	91.9	82.2-97.3	76.9	63.2-87.5	82.6	74.2-88.7	88.9	77.3-95.0	85.1	77.2-91.1	13
Reader 3	93.6	84.3-98.2	90.4	79.0-96.8	92.1	83.4-96.4	92.2	81.9-96.8	92.1	85.5-96.3	2
Reader 4	91.9	82.2-97.3	90.4	79.0-96.8	91.9	83.2-96.3	90.4	80.2-95.6	91.2	84.5-95.7	7
Reader 5	93.5	84.3-98.2	96.2	86.8-99.5	96.7	88.2-99.1	92.6	82.9-97.0	94.7	88.9-98.0	3
Pumberger M	85.1	79.2-89.8	75.2	65.7-83.3	86.8	82.4-90.3	72.4	64.8-78.9	81.7	76.8-85.9	
Neuhaus V	97.8	88.5-100.0	98.4	96.3-99.5	90.0	79.0-95.6	99.7	97.8-100.0	98.3	96.4-99.4	
Reader 1	88.2	76.1-95.6	99.7	98.2-100.0	97.8	86.4-99.7	98.1	96.0-99.1	98.0	96.0-99.2	
Reader 2	91.7	80.0-97.7	99.7	98.2-100.0	97.8	86.1-99.7	98.7	96.7-99.5	98.6	96.7-99.5	
Diekhoff T 2019 ***Without prior surgery***	79.2	70.3-86.5	70.4	56.4-82.0	84.0	77.5-88.9	63.3	53.4-72.3	76.3	68.9-82.6	
With prior surgery	46.2	26.6-66.6	66.7	22.3-95.7	85.7	64.3-95.2	22.2	12.8-35.8	50.0	31.9-68.1	
Karaca L ***Edema***	89.4	76.9-96.5	98.8	95.6-99.9	95.5	84.1-98.8	97.0	93.3-98.7	96.7	93.2-98.6	
Reader 1	91.3	72.0-98.9	99.0	94.6-100.0	95.5	74.8-99.3	98.0	93.0-99.5	97.6	93.1-99.5	
Reader 2	87.5	67.6-97.3	98.4	91.2-100.0	95.5	74.9-99.3	95.2	87.4-98.3	95.3	88.4-98.7	
Bierry G	80.8	60.7-93.5	97.5	93.7-99.3	84.0	66.2-93.4	96.9	93.4-98.6	95.1	91.0-98.0	
Thoracic	84.6	54.6-98.1	97.2	90.3-99.7	84.6	57.9-95.7	97.2	90.7-99.2	95.3	88.4-98.7	

Lumbar	76.9	46.2-95.0	97.7	91.9-99.7	83.3	55.2-95.3	96.6	91.3-98.7	95.0	88.7-98.4	
Diekhoff T 2017	87.5	47.4-99.7	100.0	78.2-100.0	100.0	100.0	93.8	70.6-99.0	95.7	78.1-99.9	
Reader 1	100.0	59.0-100.0	81.3	54.4-96.0	70.0	45.7-86.6	100.0	100.0	87.0	66.4-97.2	
Reader 2	87.5	47.4-99.7	100.0	78.2-100.0	100.0	100.0	93.8	70.6-99.0	95.7	78.1-99.9	
Reader 3	75.0	34.9-96.8	100.0	78.2-100.0	100.0	100.0	88.2	69.3-96.1	91.3	72.0-98.9	
Schwaiger BJ	95.1	83.5-99.4	88.9	65.3-98.6	95.1	84.1-98.6	88.9	67.2-96.9	93.2	83.5-98.1	
Reader 1	92.7	80.1-98.5	88.9	65.3-98.6	95.0	83.7-98.6	84.2	63.9-94.1	91.5	81.3-97.2	
Reader 2	95.1	83.5-99.4	88.9	65.3-98.6	95.1	84.1-98.6	88.9	67.2-96.9	93.2	83.5-98.1	
Foti G	88.5	77.8-95.3	92.3	81.5-97.9	93.1	84.0-97.2	87.3	77.3-93.3	90.3	83.3-95.0	
Reader 1	90.2	79.8-96.3	90.4	79.0-96.8	91.7	82.6-96.2	88.7	78.5-94.4	90.3	83.3-95.0	
Reader 2	91.8	81.6-97.2	90.4	79.0-96.8	91.8	82.7-96.2	90.4	80.2-95.6	91.2	84.2-95.6	
Petritsch B	94.1	71.3-99.9	93.8	88.6-97.1	64.0	48.3-77.2	99.3	95.3-99.9	93.9	89.0-97.0	
Wang CK	63	47.6-76.8	98.5	91.8-100.0	96.7	80.4-99.5	79.3	72.4-84.8	83.9	75.8-90.2	
Na D Before Ca2+ sub	87.5	67.6-97.3	81.2	54.4-96.0	87.5	71.4-95.2	81.2	59.4-92.8	85	70.2-94.3	
Engelhard N	83.3	62.6-95.3	53.3	26.6-78.7	74.1	61.8-83.5	66.7	42.1-84.6	71.8	55.1-85.0	
3MD- filtered back projection	75.0	53.3-90.2	66.7	38.4-88.2	78.3	62.9-88.4	62.5	43.3-78.4	71.8	55.1-85.0	

3MD - iterative reconstruction 1	87.5	67.6-97.3	60.0	32.3-83.7	77.8	64.9-86.9	75.0	49.1-90.3	76.9	60.7-88.9	
3MD - iterative reconstruction 2	87.5	67.6-97.3	60.0	32.3-83.7	77.8	64.9-86.9	75.0	49.1-90.3	76.9	60.7-88.9	
3MD - iterative reconstruction 3	87.5	67.6-97.3	66.7	38.4-88.2	80.8	66.9-89.7	76.9	52.2-91.1	79.5	63.5-90.7	
2MD – filtered back projection	4.2	0.1-21.1	93.3	68.1-99.8	50.0	6.3-93.7	37.8	34.2-41.6	38.5	23.4-55.4	
2MD - iterative reconstruction 1	8.3	1.0-27.0	100.0	78.2-100.0	100.0	100.0	40.5	37.7-43.5	43.6	27.8-60.4	
2MD - iterative reconstruction 2	20.8	7.1-42.2	100.0	78.2-100.0	100.0	100.0	44.1	39.1-49.2	51.3	34.8-67.6	
2MD - iterative reconstruction 3	37.5	18.8-59.4	68.3	51.9-81.9	40.9	25.9-57.9	65.1	56.2-73.1	56.9	44.0-69.2	
Total	86.2	83.4-88.6	91.2	89.4-92.7	85.3	82.9-87.5	91.7	90.2-93.0	89.3	87.8-90.7	

Table 14: Meta-analysis and findings for DE-CT; MD material decomposition; adaptive iterative dose reduction with different iterations: 1 mild. 2 standard. 3 strong; D/BME – Disc/ Bone Marrow Edema; TP – true positive, FP – false positive, FN – false negative, TN – true negative; CI – confidence interval [122]





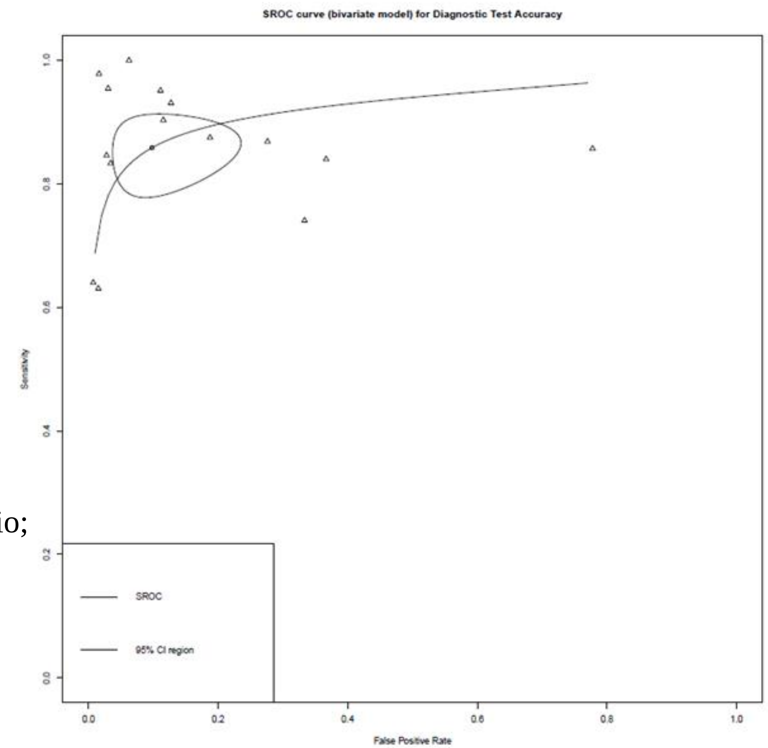
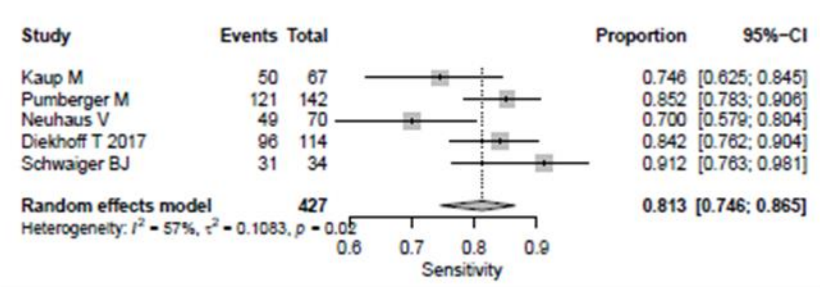


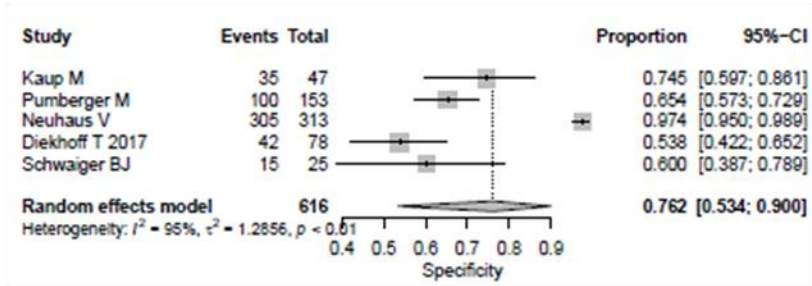
Figure 21: (a) Forest plots for sensitivity, (b) specificity and (c) diagnostic odds ratio; (d) SROC curve for diagnostic test accuracy between sensitivity and FP rate for DE-CT [122]

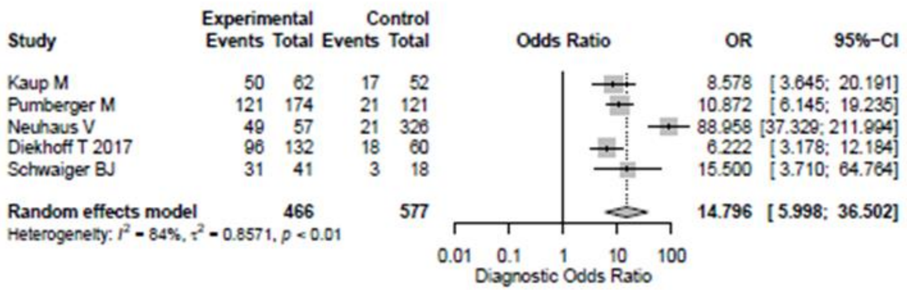
When looking for conventional CT in the identification of bone marrow respectively, disc edema the pooled sensitivity, specificity, PPN, NPV and accuracy was 81.3%, 80.7%, 74.5%, 86.1% respectively 80.9%. In contrast to DE-CT, the heterogeneity was only moderate for sensitivity (I^2=52%) and considerable for specificity and diagnostics odds (Table 15; Figure 21).

Studies		Sen	95% CI	Spec	95% CI	PPV	95% CI	NPV	95% CI	Accuracy	95% CI
Kaup M		74.6	62.5-84.5	74.5	59.7-86.1	80.7	71.5-87.4	67.3	56.9-76.2	74.6	65.6-82.3
Reader 1		79.0	66.8-88.3	40.4	27.0-54.9	61.3	55.0-67.2	61.8	47.4-74.4	61.4	51.8-70.4
Reader 2		87.1	76.2-94.3	55.8	41.3-69.5	70.1	63.0-76.4	78.4	64.5-87.9	72.8	63.7-80.7
Reader 3		82.3	70.5-90.8	78.8	65.3-88.9	82.3	73.0-88.8	78.8	68.2-86.6	80.7	72.3-87.5
Reader 4		74.2	61.5-84.5	78.8	65.3-88.9	80.7	70.8-87.8	71.9	62.2-80.0	76.3	67.4-83.8
Reader 5		79.0	66.8-88.3	83.0	70.2-91.9	84.5	74.8-90.9	77.2	67.3-84.8	80.9	72.5-87.6
Pumberger M		69.5	62.1-76.3	82.6	74.7-88.9	85.2	79.4-89.6	65.4	59.8-70.6	74.9	69.6-79.8
Neuhaus V		86.0	74.2-93.7	93.6	90.3-96.0	70.0	60.4-78.1	97.4	95.3-98.6	92.4	89.3-94.9
Diekhoff T 2017		72.7	61.3-80.1	70.0	56.8-81.2	84.2	78.1-88.8	53.8	45.8-61.7	71.9	65.0-78.1
Schwaiger BJ		91.2	76.3-98.1	60.0	38.7-78.9	75.6	65.5-83.5	83.3	61.8-93.9	78.0	65.3-87.7
Reader 1		75.6	59.7-87.6	77.8	52.4-93.6	88.6	76.2-94.9	58.3	43.6-71.7	76.3	63.4-86.4
Reader 2		73.2	57.1-85.8	83.3	58.6-96.4	90.9	77.8-96.6	57.7	44.1-70.2	76.3	63.4-86.4
Total		81.3	77.2-84.9	80.7	77.3-83.7	74.5	71.2-77.5	86.1	83.6-88.4	80.9	78.4-83.3

Table 15: Individual findings for sensitivity, specificity, PPV, NPV and accuracy for Computed Tomographies; D/BME – Disc/ Bone marrow Edema [122]







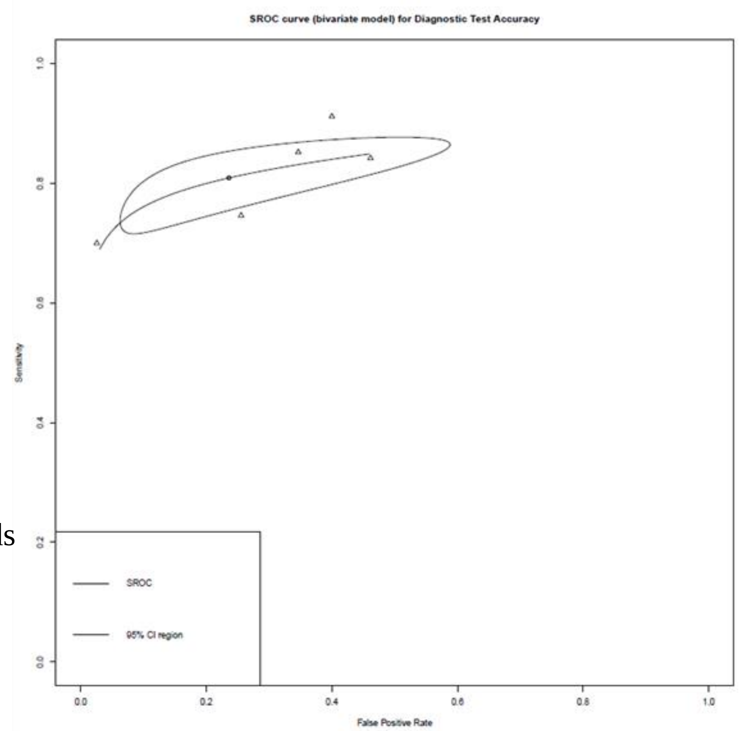


Figure 22: (a) Forest plots for sensitivity, (b) specificity and (c) diagnostic odds ratio; (d) SROC curve for diagnostic test accuracy between sensitivity and false positive rate for CT [122]

When comparing both diagnostic tools significant differences were found for specificity ($p<0.001$) and accuracy ($p=0.023$), however not for sensitivity ($p=0.119$).

4.5.2 Implementation of DE-CT in clinics

In patients where MRI is limited by metal implants, availability, cardio-pulmonary instability such as in trauma patients or claustrophobia DE-CT can be a reasonable alternative to MRI. Especially in non-displaced spine trauma where discoligamentous injuries need to be excluded

Hereby, the sensitivity was reported at 99.6%, specificity at 86.7% and accuracy at 97.2% in the lumbar spine with higher accuracy especially in the lower lumbar levels [135].

Other new approaches are the application of reconstruction algorithms after calcium subtraction with higher sensitivity of 91.7% compared to without calcium subtraction of 87.5% [136]. Additionally, three material decomposition algorithm is found to be better than two material decomposition algorithm [137].

Other important factors are the time elapsed between accident and time of imaging where the sensitivity increased if the interval was more than 2 days [138] as well as the inter-observer reliability which ranged from 0.51-0.96 [126], [129], [127], [132]. Hereby, a greater inter-observer variation was observed in patients with intact pars interarticularis [139].

4.6 New findings

Based on our studies new findings were observed which can be summarized according to our objectives (chapter 2): Due to increasing popularity in the last years, the studies provide evidences of the logistical difficulties, variety of injury pattern, severity related to the aerial sports as well as related concomitant injuries and therefore subsequent surveillance and treatment. Furthermore, new algorithms can be developed from the current literature on spinopelvic dissociation.

1.a. We showed that most patients suffering from airborne sports injuries were primarily admitted to our hospital (n=155/235, or 67.0%) by helicopter, followed by ambulance and self-admission. For those suffering from spinal injuries the rate was even higher with 81.8% (n=121/148), respectively for the sacral fracture group with 79.5% of cases (n=35/44).

1.b. Initial diagnostics were primarily performed in the resuscitation room in 162 cases (n=162/235, 68.9%) among all patients and since spinal injuries are commonly associated with severe concomitant injuries, 75.0% of all patients suffering from spinal injuries (n=111/148), respectively 81.8% (n=36/44) of patients with sacral injuries were primarily examined in the resuscitation room.

2.a. In total, 235 patients met inclusion criteria at a mean age of 38.7 years (min/ max 18 -74) and predominantly male were affected in 82.6% (n=194/235). Three of the patients had to be resuscitated after onset of a PEA of which two patients deceased. The most common aerial sport performed was Paragliding (n=192, 82.6%, including 13 tandem Paraglider), followed by BASE-jumping, Skydiving (one tandem-Skydiver), Speedflying and Delta flying.

2.b. Especially the spine is affected in 63.0% of cases (n=148/235) suffering from 334 spine injuries due to a high-energy trauma whereas sacral injuries occurred in 18.7% (n=44/235) of patients. Of the 44 sacral fractures only 16 patients suffered from spinopelvic dissociation (n=16/44, 36.4%).

2.c. In the spine group extremity injuries were most common with 32.4% (n=48/148) of cases, following thoracal injuries in 31.8% (n=47/148), head/face injuries in 18.2% (n=27/148) and pelvic lesions (17.6%, n=26/148). In the spinopelvic dissociation group especially concomitant pelvis and spine injuries were observed in 87.5% (n=14/16), respectively 75.0% (n=12/16), followed by extremity injuries in 68.8% (n=11/16), thoracal injuries in 50.0% and intra-abdominal bleedings in 37.5%.

3.a. Overall, the ISS was 16.5 compared to the spine group with 17.9. For the spinopelvic dissociation group a mean ISS of 38.1 was observed. Furthermore, highest ISS was observed at the age between 50 and 60 years with 27.6. When looking for the different aerial sports this was highest in the BASE-jumping group with 21.1 (13.9) followed by Speedflying with 19.8 (8.8) and Delta Flying with 18 (14).

3.b. In the spine group 20.9% suffered from neurological impairment (n=31/148), whereas in the spinopelvic dissociation group this was 25.0% (n=4/16).

4.a. Among all patients, 55 patients (23.4%; n=55/235) required an immediate emergency surgery and in another 61 patients surgery was scheduled within the next few days (26.0%; n=61/235). In addition to the 55 patients who underwent emergency surgery 11 patients were transferred to the intensive care unit. 111 patients were hospitalized on the general ward and 47 patients were treated as outpatient.

4.b. For the spine group, surgery was performed in 54.5% due to instability or neurological impairment. Especially open posterior spondylodesis with 67.9% was performed followed by percutaneous posterior stabilization in 21.8% of cases (n=17/78), and eight stand-alone anterior spondylodesis with cage and plate (n=8/78, 10.3%). For the sacral fracture group a majority of cases was treated conservatively 71.4% (n=20/28), whereas in the spinopelvic dissociation group 14 of 16 patients underwent surgical stabilization. Hereby, percutaneous iliosacral screw stabilization was prioritized in 43.8% (n=7/16) and in another 37.5% of cases a triangular stabilization (n=6/16) either bilateral (n=4) or unilateral in two cases (n=2).

5.a. Patients suffering from spinopelvic dissociation are typically young at a mean age of 31.6 ± 11.6 years and gender is nearly equally distributed with 49.3% being male.

Because of a high rate of neurological impairment in 73.1% (n=258/353) an open reduction was performed in 61.2% (n=216/353) and especially triangular fixation (TF) was used in 68.8% (n=243/353). However, despite the surgical fixation technique the overall union rate was 100% (n=307/307).

5.b. Based on the findings in the literature we recommend open reduction including wide decompression laminectomy within 48 hours if neurological impairment is present and patient is stable enough. For stabilization we recommend triangular posterior fixation which allows best visualization of the fractures and therefore reduction and decompression.

6.a. To identify potentially discoligamentous injuries DE-CT is a good alternative to MRI especially in cardio-pulmonary unstable patients. Hereby, we found an overall sensitivity and specificity of 86.2% respectively 91.2% compared to 81.3% (p=0.119) and 74.5% ($p<0.005$) for conventional CT. Likewise the sensitivity the accuracy was significant higher for DE-CT with 89.3% compared to 80.9% (p=0.023).

5. Discussion

Based on our hypothesis we noted that patients were rather mid-age at a mean age of 38.7 years and predominantly male patients in 82.6%. Further our hypothesis can be confirmed, that airborne sports patients typically presented with a mean ISS of 16.5 and spine injuries is the most common affected body part in 63.0% (n=148/235). On the other side the incidence of spinopelvic dissociation was 14.0% (n=33/235) including 16 spinopelvic dissociations. Based on the systematic reviews we were able to show that DE-CT is a good alternative especially in potentially unstable patients with an overall accuracy of 89.3% compared to 80.9% for conventional CT. Finally, between 1969 and 2018 only 50 studies were published on spinopelvic dissociations. Based on the studies, we developed an algorithm recommending triangular fixation and open wide decompression laminectomy in patients with neurological impairment within 48 hours after the accident.

5.1 Epidemiology

In traumatized patients approximately 30.2% of patients suffer from spine fractures in high-energy trauma. The overall incidence of spine fractures is described to be 64 per 1 million patients and for sacral transverse fractures between 3% and 5% [140]. U-type fractures are even less frequently with a rate of occurrence in 2.9% from patients with pelvic ring fractures [44]. When looking for sports related spine injuries the most common causes are cycling, winter sports and climbing. Hereby, airborne sports are ranked as number 25 with an incidence of 16.2% [48], [141].

In airborne sports the mortality for BASE jumping is highest with one per 2,317 jumps and for Paragliding 45 per 100,000 jumps, respectively [142], [143]. Especially the thoracolumbar spine, pelvis and lumbopelvic junction are affected. When looking for concomitant neurological impairment this is associated between 10 to 30% of traumatic cases. Hereby, the incidence in neurological impairment is significantly higher for spinopelvic dissociation with 68.1% compared to 11.2% in traumatic spine fractures [144], [145], [39]. Other airborne sports related injuries include thoracic, abdominal, upper and lower extremity injuries. Rather seldom injuries include vascular injuries such as rupture or dissection which have been reported in case reports [146].

For causes of airborne sports most are related to pilot errors and rapid changes in weather or bad weather conditions in 53.5% respectively 10.1% of cases [147]. Because of a fragile Paragliding parachute, it collapses easily and once it is deflated it is difficult to re-inflate and re-balance. This explains, why pilots are especially at risk during take-off which includes the running and inflation phase (35.1%) or landing (48.7%) because of the close distance to the ground [148], [149]. Furthermore, although students are given instruction to activate the reserve parachute, there is not much time to pull it from low height. Likewise, in Skydiving a proper landing technique is pivotal to avoid injuries [150].

Comparing our results with the current literature we noted an increase in age from 37.0 years to 39.4 years in airborne sport pilots [51], [151]. Additionally, the ISS was much higher than previously reported with 17.9 compared to 8.0 [51]. This may be caused by a selection bias since we performed our study at a level-1 trauma center where preferably polytraumatized patients are admitted to by rescue helicopters. When looking for the individual aerial sports performed, highest ISS was observed for BASE-jumping (21.1), followed by Speedflying (19.8), Delta flying (18.0) and Paragliding (16.0). This may be caused due to the different positioning of pilots. Paragliding athletes are located in a sitting position and travel at a slower speed than in other disciplines. Furthermore, the parachute is most instable in starting and landing attempts which rather causes a fall from low height with protection to head and thorax, whereas in BASE-jumping and Speedflying pilots want to fly as fast as possible and taking more risks for the experience. This also explains, why BASE-jumper and Speedflyer are rather of young age (30.8 years for BASE-jumping, respectively 33.3 years for Speedflying). For age, highest ISS was 27.6 in the age group between 50 and 60 years. This may be related to the level of experience who are willing to take more risks and if any accidents occurs these are more likely to suffer from severe injuries. In addition, those patients may have osteopenia and therefore are more vulnerable for severe injuries. On the other side, older patients are more careful and less willing to take risks for extreme maneuvers. In contrast to airborne sports, the overall ISS was found to be 2.2 (2.2) with a mortality rate of 0.03% and the incidence of severe injuries in winter sports was 0.229 per million rides per year [152]. Based on the sort of sport, the type of injury may differ. In Paragliding and Speedflying especially the spine is affected with 51.5% respectively 45.8% of cases [150], [153]. Skiing and contact sports athletes are suffering more from head injuries, whereas rock climbers preferably break the spine and sacrum [154]. In addition, a shifted ratio in gender can be observed related to the ISS group. With increase in ISS, males are more affected with 1.69:1 at ISS between 12-14, 1.86:1 at ISS between 16-24 and 1.95:1 at ISS more than 24 [155].

In motorcycling the age is younger, 38.7 years and the ISS is 7.7±6.7. For the location of injuries a peak was identified for rib fractures and maxillofacial trauma (2.5%, respectively 11.6%) [156]. In snowboarding the lower as well as upper extremities are at risk such as anterior cruciate ligament tears, distal radius fractures and knee sprains. Furthermore, closed head injuries are common, with only few lumbar strains without fractures [157]. In terms of vertebral fracture the most affected vertebral body is located at the thoracolumbar region [48], [158], [154]. In cycling or motocross, the cervical spine (C5/6) is most often injured from falling to front over the handlebar resulting in an hyperextension.

5.2 Trauma management

The ABCDE algorithm allows a prompt, feasible, fast assessment and precise identification of acute life-threatening injuries. If a cardiopulmonary resuscitation is required, a PEA can be found most commonly, especially in polytraumatized patients rather than a myocardial infarction or asystolia. For cardiopulmonary resuscitation (CPR), CPR devices should be discussed critically. The use of the autopulse device requires a secure placement to reduce iatrogenic injuries such as organ lacerations and hinders ventilation [159], [56] because of the thoracic compression which we reported in our study ‘Dead or Dying?’ [160]. In some cases this may worsen the situation, why manual CPR should be prioritized. For precise monitoring of blood pressure an arterial access is helpful which allows invasive registration, although, it is time intensive. In addition, in unstable patients an early transfusion protocol should be started since the blood loss is rather underestimated by the treating physician [160].

Besides a focused assessment with sonography for trauma a LODOX which takes approximately 13 seconds and allows to prioritize injuries. The level of radiation is 94% lower than a conventional X-ray [59], [161] and life-threating as well as dislocated injuries can be therefore excluded and triaging patients accurately [60], [162]. Hereby, the overrating of triage is much higher than 50%, whereas undertriage is less than 5% especially in mass disaster [163]. According to Rosedale, it lowered undertriage rates by 10.8% and overtriage rates by 4% [164].

In the further management FAST is performed which requires experienced readers, although until today it is not clearly defined. In 1999, it was specified for someone who performed at least 200 supervised sonographies with a high learning curve especially during the first 10 with high accuracy after 25 to 50 examinations [165], [166]. When comparing the sensitivity of FAST for detection of solid organ injuries this was nearly double for the experienced group compared to the less experienced ones [61], [167]. The accuracy in experienced readers following the quality assessment of diagnostics were investigated by Lee et al. based on a systematic review. The authors showed a sensitivity of 92.1% (87.8%-95.6%), specificity of 98.7% (96.0%-99.9%), with positive predictive value of 90.7% (70.0%-98.0%), respectively negative predictive value of 98.9% (98.1%-99.5%) for intra-abdominal injuries compared to the gold standard, a CT scan [168].

When comparing X-rays of the thorax and pelvis compared to CT, the CT scan has become the gold standard because of the easiness and quick availability, which enables to exclude fractures, organ lesions and severe bleedings (brain, abdominal, thoracal, pelvic) with an angiography. For scanning it takes about 30 seconds and shows only few artefacts [169]. Furthermore, plain radiography shows less accuracy compared to CT scan in poly trauma management. For cervical spine injuries CT scan identifies approximately 37.5% which would have been missed otherwise in X-ray. For example for thoracolumbar fractures the incidence is lower with 14.0% of cases [169]. Especially patients who consumed alcohol may not suffer from pain, thus CT scan should be performed [170].

In suspected soft tissue damages to the ligaments and tendons of the spine as well as spinal cord the most sensitive diagnostic tool is the MRI and the dual-energy CT [122]. However, MRI scan is not suitable for the acute trauma care setting since it takes up to 30min for a whole spine MRI and it is unknown if the polytraumatized patient has any magnetic implants. In contrast DE-CT is fast accessible, time saving and can be used in the emergency department if available. Studies have shown a high diagnostic accuracy with sensitivity of 86.2% and specificity of 91.2% [123], [171], [122]. Authors therefore concluded that patients who are unable to undergo MRI could benefit from this capability. However, there are some limitations. Since DE-CT bases the reconstructions the age of patients may have a major impact due to the decrease in water content in the nucleus pulposus. The collagen content is also affected by the affected region as this is higher in thoracic disks compared to lumbar ones. As well and the readers experience has a major influence [123], [172].

5.3 Treatment

After diagnostics the correct treatment is essential. Since spine fractures comprise an estimated 6% of all fractures, the indication and surgical timing is very important to maximize the functional outcome. Therefore, O'Boynick et al. investigated the necessity of early surgery [173]. In total, 2,000 neurosurgeons were interviewed and asked about early versus delayed surgery and 80% of neurosurgeons supported early fixation but less than half of the group recommended fixation within 24 hours of admission [174]. The authors attributed the difference with lack of resources during weekend and overnight. Furthermore, a decrease in long-term paralysis especially in patients with spinal cord injuries was observed in 33% of patients. Other than that pulmonary complications such as pneumonia were reduced. One predicting factor was the number of cases performed at the institution [175]. Besides functional outcome and complication rate a decrease in costs can be seen for early surgical thoracolumbar trauma surgery compared to delayed ones. This ranged between $40,000 and $80,000 per patient in 2013 [173].

A variety of different fixation methods have been described. The most common type of fixation is posterior stabilization which can be performed either open or percutaneously.

An anterior fixation is especially in highly comminuted and unstable fractures recommended. Overall, the anterior stabilization shows better maintenance of thoracic kyphosis compared to posterior stabilization [176]. For posterior screw stabilization, different techniques exist. These include free hand pedicle as well as robot-assisted screw placement.

Besides pedicle screw placement – open, percutaneously or robot assisted –, current research focuses on cortical bone trajectory (CBT) [177], [178]. In theory, these have improved initial fixation by optimizing contact of the cortical bone as well as reduce the risk of neurovascular injuries because of only little soft tissue dissection [179]. The insertion of the CBT starts at the junction between the lateral pars interarticularis and superior articular process. In our opinion, this technique should rather be used for revision procedure such as after screw cut out or implant failure than for primary fixation (Figure 22). In addition, as shown in one of our studies, a learning curve for new techniques such as robot assisted screw placement needs to be considered [180].

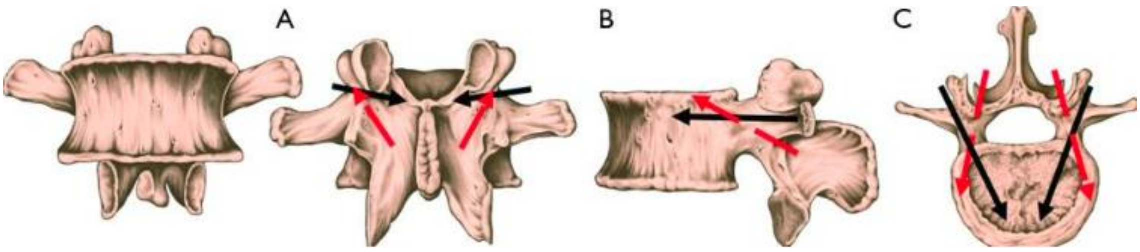


Figure 23: Cortical Bone Trajectory (red arrows) versus traditional pedicle screw placement (black arrows) [181]

Regardless the method of screw placement, in patients with traumatic spinal stenosis an additional decompression such as laminectomy or application of systemic steroids should be performed. Steroids, methylprednisolone application within 8 hours of acute spinal cord injury has shown improved neurological outcomes compared to placebo 1 year after accident, although recent studies did not show any benefits from it [182], [183], [184]. Another medical drug is GM-1 ganglioside which may have significant benefit in outcome 6 months after, however, the literature is limited [185]. If no pharmaceutical application is thought there are ongoing discussions on the timing as well as necessity of surgical decompression. Some authors recommend to perform acute decompression [186], whereas Cengiz et al. found no significant neurologic benefit of cervical spine cord decompression between less than 72 hours and more than 5 days after accident [187]. Furthermore, a systematic review suggested even decompression within 24h to reduce complications and improve neurological outcome [188].

Nowadays, there is clinical evidence that early surgical decompression within 24 hours, and especially within 8 hours of acute spinal cord injury is safe, more cost- effective, shows better neurological recovery and reduces secondary injury mechanisms [188]. Besides the traditional form of total laminectomy and flavectomy, intradural decompression – durotomy – has been reported [189]. The risk of complication is much higher including pseudo-meningoceles, low-pressure headaches and quadriplegia although it is rare [190], [191]. Currently, some authors hypothesize that the damage of the spinal cord comes especially from the secondary injury rather than the initial accident and early decompression allows to reduce the risk of secondary injury [188], [192], [193].

For spinopelvic dissociation the procedures vary from conservative treatment to percutaneous iliosacral screw fixation, posterior tension band, bridge plating or triangular spinopelvic fixation [87]. Conservative treatment should only be considered in patients who are unable to non-weightbear or are bedbound for at least three months and would not tolerate surgery [96], [194]. Further variations in treatment include iliosacral screw fixation, external fixation [108], ventrodorsal stabilization [30] or triangular fixation with cage implantation (Figure 23) [84]. Hereby, iliosacral screw fixtion can be divided into trans-iliosacral or two iliosacral screws. Regardless the method of choice for the osteosynthesis of spinopelvic dissociation the injury healing rate – fusion of the spinopelvic dissociation and radiographic union of the sacral fracture – is reported with 100%.

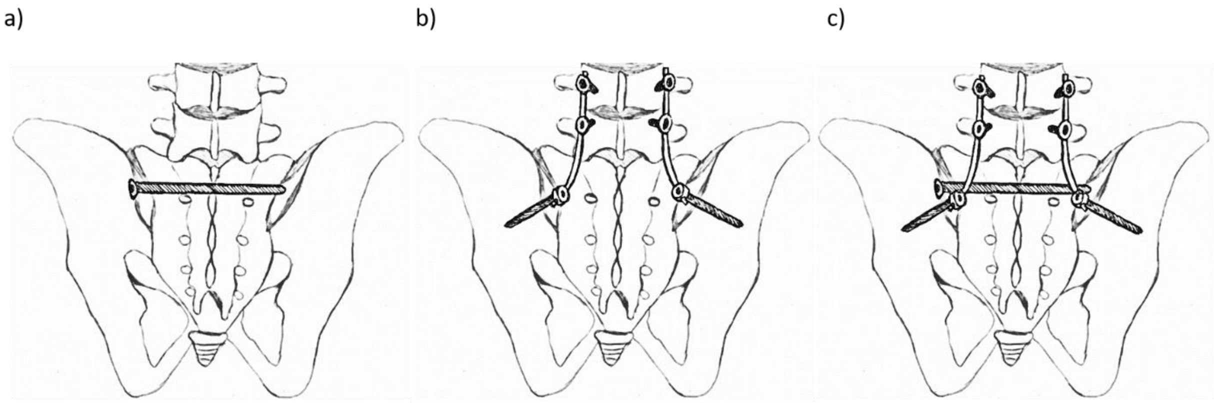


Figure 24: Methods of spinopelvic dissociation fixation; a) iliosacral screw fixation, b) bilateral triangular fixation, c) combined triangular and iliosacral screw fixation [70]

When looking for biomechanical studies under cyclic loading the most stable technique and best results can be found for triangular spinopelvic fixation compared to iliosacral screw fixation [76], [195]. The overall complication rate is at approximately 29.9% [75], [196]. This includes healing respectively fusion rate with 9.3% [197], [198], infection with 36.5%, implant failure in 25.0% and wound healing issues in 14.6%. Other rare incidents may include acute bleeding from the superior gluteal artery, deep vein thrombosis or progression of kyphosis. To lower complication rate such as blood loss and infection rate percutaneous spinopelvic fixation is recommended, although no difference in operating time was identified [81]. In contrast, this technique does limit the reduction in displaced fractures with a kyphosis of more than 30° which is typically the case in U-type fractures [44], [121], [115]. However, the infection rate correlates with the type of fixation which was significantly higher for open compared to percutenous osteosynthesis (3.4% to 5.9%) [197], [198]. One study described a significant reduction in blood loss without other differences in complication rate and surgery time for percutaneous procedures [81]. Other risk factors are the necessity of ICU hospitalization which is most likely in these kind of injuries as they are correlated with high energetic traumas and polytraumatized patients [199].

Because of the high rate of neurologic deficits a reduction with or without decompression should be considered in patients. For fractures with complete stenosis of the spinal canal or intraforaminal fragments the method of choice is a sacral laminectomy regardless of the presence of neurological impairment [82], [80]. In transverse sacral fracture, root transection is present in about 35% of cases [200]. In regards of time the decompression should be performed as early as possible (within 24 hours) to lower the complication rate and improve recovery of neurological deficits [144], [145]. Therefore, we developed and published an algorithm for the treatment of spinopelvic dissociation (Figure 24).

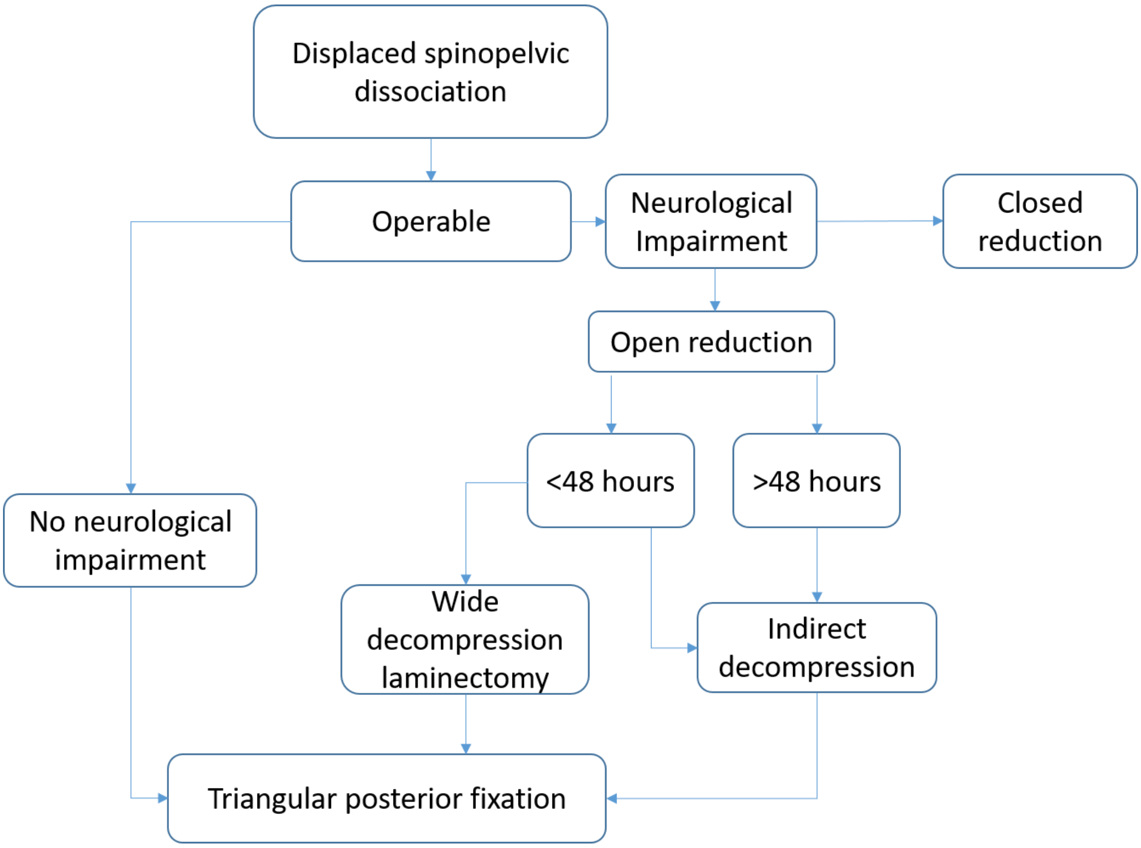


Figure 25: Treatment algorithm for patients with spinopelvic dissociation [70]

5.4 Anticoagulation after spinal injuries

After surgery with or without acute spinal cord injury anticoagulation is required to prevent a thromboembolic event. Especially people with spinal cord injury are at risk for deep venous thrombosis because of neurological dysfunction, immobilization, intimal injury and hypercoagulability. On the other side, surgery causes extensive tissue damage which may cause hemorrhage or bleeding which could be worsen by initiating early anticoagulation [201]. The Paralyzed Veterans of America developed guidelines which recommend the early use of mechanical compression devices, followed by low-molecular weight heparin including intermittent pneumatic compression. In polytraumatized patients who suffered from intracranial bleeding, perispinal hematoma and/ or hemothorax the usage of pharmaceutical anticoagulation is forbidden until the patient is stabilized. In those patients a cava vein filter may be applied if an acute bleeding persists for more than 72 hours [202]. Other possibilities include rotating beds, electrical stimulation or combination of different modalities. Once pharmaceutical anticoagulation is started, a three-month duration should be performed [203], [204], [205].

5.5 Rehabilitation

Finally, after primary care in the emergency room including diagnostics and medical examination followed by operative or conservative treatment and prevention from further complications such as thromboembolism, rehabilitation is essential. Ideally this should start once a patient is stabilized in hospital and allows to prevent from secondary complications including thromboembolism or decubitus. The aim is to improve patient's independence and activity, return to daily and recreational activities and finally reintegration into society.

In the acute phase the focus is on prevention of secondary complications, psychological rehabilitation, promoting neurorecovery and improving function, whereas in the chronic phase compensatory and assistive approaches are helpful. Since spinal cord injury confronts patients with life-altering events this is a long lasting process [206], [207]. Because of the complexity and variability in injuries no optimal, standardized strategy exists. Individual adjustments are required and multiple treatments have to be combined. It should be focused on the prevention of ulcers, preservation of limb function, respiratory management, sexuality and bladder management [205], [208]. This may include psychological treatment, physical training, environmental adaptations, pharmaceutical adjustments including painkillers or bronchodilative, alpha blockers medications, mechanical ventilation or even further surgeries – i.e. transurethral sphincterotomy, tendotomies, tendon transfers, indwelling catherization. It has to be mentioned that the rehabilitation process is a lifelong process which requires intensive and multidisciplinary rehabilitation [205].

5.6 Airborne sports injury prevention

The presented studies illustrate the most common injuries resulting from high-energy airborne related trauma and correlated issues. In the recent years, protectors have been developed and rescue parachutes are recommended for Paragliding. These protectors can decrease the incidence of spine and sacral injuries even though most injuries occur during the take-off and landing phase. Furthermore, new special glides were developed which are wider and allow more stability. These ones should be considered especially for beginners and intermediates.

Besides improvement in technologies and protectors first responders such as pilots and associates have to be trained about the type of injuries, severity, risk factors and life support. This enables a prompt and sufficient identification of life threatening disease, primary stabilization and reduces the risk of further complications from unnecessary movement until the paramedics arrive at the scene.

5.7 Algorithm in airborne sports patients

Based on the findings of our individual studies and the extensive literature search outlined in this thesis we were able to develop an algorithm for patients following airborne sports injuries with focus on spine and spinopelvic dissociation (Figure 25).

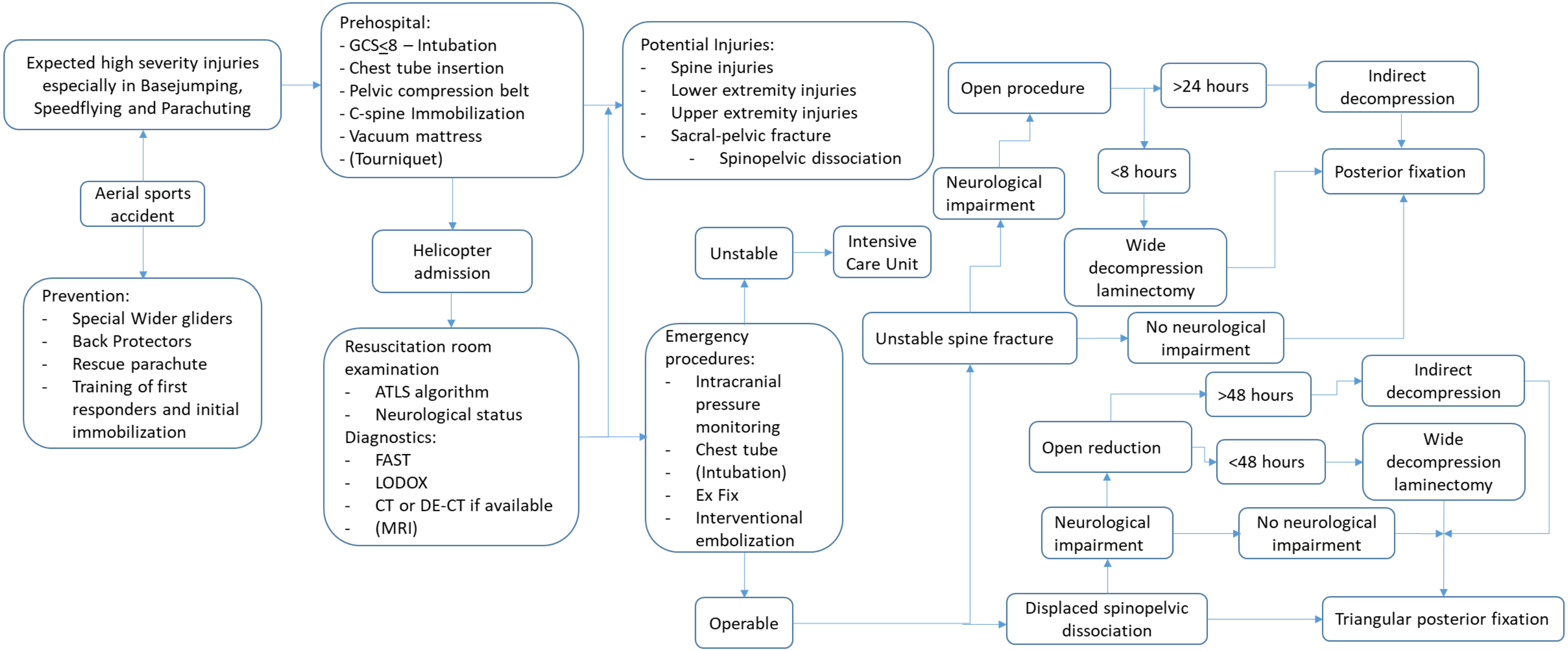


Figure 26: Algorithm of aerial sports accidents and subsequent treatment based on the findings in this thesis. Prevention should be performed prior performing airborne sports and athletes should be aware of the risks. If an accident occurs a helicopter should be requested as pilots are typically landing in difficult area allowing quicker search and admission to the hospital. Patients should be admitted through the trauma room involving neurosurgeons, trauma and orthopaedic surgeons, interventional radiologists. If the patient is stable surgery is recommended where patients with any neurological impairment less than 48 hours or severe deficit greater than 48 hours is recommended.

5.8 Limitations

All studies have some limitations which should be mentioned. Since the studies are of retrospective design no further mid- to longterm follow-up was assessed. The airborne sports studies were performed at a level 1 trauma center why especially severe injured patients are transferred to this center, whereas patients with isolated trauma of less severity are admitted to smaller hospitals close to the place of accident. Moreover, some patients were transferred from smaller centers. Since we only investigated the intrahospital management, injury pattern, mortality and subsequent treatment, no conclusion on the overall mortality was made as some patients may have died at the trauma site. Although the different classifications AO Spine, Denis, Roy Camille are good and reliable there is a low inter-observer reliability. For the AO spine classification with thoracolumbar fractures this was reported to be between 0.69 and 0.90 [209]. Similar results are likely for the other classifications. To minimize the bias all X-rays, LODOX imaging and CT scans were evaluated by the author of this thesis and the articles. In patients with suspected neurological impairment, routinely no MRI performed since this is a time consuming diagnostic tool to identify the predisposition of disc hernia and therefore pre-existing neurological impairment such as dysesthesia were difficult to identify. To minimize this bias a comprehensive review with the patient was performed once they were awake and responsive. For spinopelvic dissociation because of the rare nature, there is a dearth in literature and only little is known. When looking for the systematic review on spinopelvic dissociation, most studies were case reports in 38% (n=19/50) and only 16 articles presented between 1 and 10 patients (32%, n=16/50).

6. Conclusions

Our studies investigate the airborne sports related injuries as well as high-energetic related spine fractures which are underreported and require early, prompt and appropriate treatment. Additionally, we were able to show that DE-CT is a good diagnostic tool which should be implemented in the emergency setting to diagnose discoligamentous spine injuries. The pooled sensitivity and specificity was found to be 86.2% respectively 91.2% with a PPV of 85.3% and NPV of 91.7%. The overall accuracy was 89.3% and the heterogeneity was found be considerable (I^2>70%) in all cases. Additionally, the sensitivity and accuracy was significantly higher compared to conventional CT for bone marrow and disc edema. As also outlined in the systematic review on spinopelvic dissociation it is a rare injury where patients suffer from significantly more severe concomitant injuries and therefore higher ISS with 38.1 in the spinopelvic dissociation group compared to other patients. For aerial sports the ISS was highest in BASE-jumping with 21.1 which requires highest awareness of all treating physicians to provide prompt and sufficient diagnosis and subsequent treatment. The incidence of spine injuries was found to be 63.0% of which especially the thoracolumbar region was affected and A0 fractures were most commonly observed. Sacral fractures were less common with an incidence of 18.7% however, 36.4% of cases suffered from spinopelvic dissociation. This incidence was significantly higher compared to the literature. Neurological deficit was observed in 25% of patients with spinopelvic fractures which was significantly lower compared to the literature with 68.1% in mean based on our meta-analysis. In spine fractures this was as low as 20.9%. Furthermore, we recognized limitations in literature on the trauma algorithms, treatment algorithm especially for spinopelvic dissociation and post hospital management. Because of the lack of treatment algorithm and the knowledge we gained in the individual studies we were able to developed an algorithm for the diagnostics and treatment in airborne sports patients and published a surgeon’s decision making for the fixation technique and in the necessity of additional decompression in spinopelvic dissociation. Further research is required to develop guidelines not only for patients who suffer from spine injuries or spinopelvic dissociation but also more general for polytraumatized patients, the postoperative setting and the rehabilitation process.

Our results can be used to sensitize emergency physicians and offer prevention courses to athletes to make them aware and informed about the potential risks of airborne sports. This allows to improve and facilitates the recognition of discoligamentous injuries, current standards in treatment – the necessity of new ones compared to established ones –, rehabilitation, postoperative care as well as the trauma management. If a BASE-jumping accident is reported and admitted to the hospital, the emergency physicians must warrant for life-threatening injuries and subsequent emergency interventions to avoid any delay. Improvements in trauma management include a good location of the resuscitation room close to intensive care unit, operative room and helicopter spaces and a well-rehearsed, interdisciplinary team with one resuscitation room manager to facilitate a structured, prompt and early diagnosis with a low dose (full) body X-ray, Dual-Energy-Computed Tomography and focused assessment with sonography for trauma (FAST). This could be a resuscitation room with a Dual-Energy-Computed Tomography and operative space for life-saving measures such as external fixation of the pelvis and limbs, pelvic packing, thoracic or ventricle drainages as well as in unstable patients the possibility for thoracotomy or laparotomy. Once the patient is stabilized an interdisciplinary intensive care treatment is required including neurosurgeons, orthopaedic and trauma surgeons, specialists for internal medicine as well as intensive care medicine, and if possible physical medicine and rehabilitation physicians. This will enable an early initiation of rehabilitation and postoperative care including mobilization and psychological counseling.

7. Summary in English

Introduction: High energetic airborne sports accidents can cause severe injuries such as spine injuries as well as spinopelvic dissociation however; there is a dearth in literature.

Purpose: The purpose of this thesis was to investigate (1) the type and severity of different injuries (2) with focus on spinal fractures and (3) spinopelvic dissociation in airborne sports. Furthermore, we were interested in the trauma management including (4) the specificity, sensitivity and accuracy of DE-CT for discoligamentous injuries and (5) performed a literature search on spinopelvic dissociation investigating the etiology and variety of treatments to establish a treatment algorithm.

Methods: Therefore, a retrospective chart review of patients who were admitted to a level I trauma center between 2010 and 2017 was performed. All charts and radiographic findings were analysed and classified by the author of this thesis. Finally two systematic reviews were conducted to analyze the current knowledge on spinopelvic dissociation and Dual-Energy-Computed Tomography.

Results: In total, 235 patients were admitted to the emergency department due to an airborne injury at a mean age of 38.7 years. In total, 148 patients (148/235, 63.0%) suffered from 334 spinal fractures and 5 spinal contusions and 44 patients (18.7%) presented with sacral fractures, including 16 spinopelvic dissociations (36.4%). For treatment 78 patients (54.5%, or 78/148) with spine injuries and 87.5% of spinopelvic dissociation patients underwent subsequent surgical stabilization. Because of the limited literature on spinopelvic dissociation and only 50 publications investigating 379 patients we developed an algorithm for treatment. On DE-CT a total of 13 studies were found which showed a significantly higher pooled sensitivity and accuracy and positive trend in specificity.

Conclusions: Highly severe, even life-threatening injuries in airborne sports such as thoracolumbar fractures are reported. Additionally, the incidence of spinopelvic dissociation per sacral fractures (36.4%, 16/44) is extremely high. To facilitate diagnostics and treatment DE-CT should be used in patients with suspected discoligamentous injuries and we developed an algorithm for the setting of airborne sports patients.

8. Summary in Hungarian

Bevezetés: A nagy energiájú légi sportbalesetekben olyan súlyos sérüléseket elszenvedhetnek mint a gerinc sérülések és spinopelvicus disszosziációk, az ilyen sérülésekkel kapcsolatos nemzetközi irodalom azonban nem túl gazdag.

Cél: A légi sportban a sérülések típusának és súlyosságának vizsgálata (1), különös figyelmet szentelve a csigolya töréseknek(2) és a spinopelvicus disszociációknak (3) Cél továbbá a traumatológiai eljárás során a discoligamentáris sérülésekben a DE-CT specificitásának(4) szenzitivitásának(5) és megállapítása, illetve egy olyan irodalmi áttekintés készítése mely a spinopelvicus disszociáció etiológiájának és különböző kezelési eljárásainak áttekintésével alkalmas egy kezelési algoritmus kialakítására.

Módszerek: Retrospektíven vizsgálatam azokat a betegeket, akiket egy I. szintű traumatológiai centrumban elláttak 2010 és 2017 között. A betegek adatlapjainak és radiológiai felvételeinek kiértékelését a tézis szerzője végezte. Végül két irodalmi áttekintésben foglaltam össze a Dual Energy CT használatát spinopelvicus disszosziációkban.

Eredmények: összesen 235 sportolót, (átlag életkor 38,7 év) láttak el az egyetem sürgősségi részlegén légi sportban elszenvedett sérülések miatt. 148 beteg szenvedett gerinc sérülést (148/235, 63,0%) , ebből 334 csigolya törést és 5 gerinc zúzódást, 44 beteg (18,7%) szenvedett csigolya törést a sacralis régióban, ebből 16 járt spinopelvikus disszociációval (36,4%) 78 gerinc sérült beteg (54,5% vagy 78/148) gerincét stabilizálták operatív úton. A rendelkezésre álló csekély irodalmi adat (50 cikk mely összesen 379 beteget vizsgált) miatt kialakítottunk egy kezelési algoritmust. A DE-CT-n végzett irodalmi áttekintés során a tanulmányozott 13 cikk magasabb szenzitivitást pontosságot és egy pozitív trended állapított meg a specificitás területén is.

Következtetések: Rendkívül súlyos, akár még az életet is veszélyeztető sérülésekkel - mint a thoracolumbalis szakasz töréseivel - is találkozhatunk a légi sportokban. A spinopelvicus disszosziáció sacralis csigolyaszakasz töréseihez viszonyított aránya (36.4% 16/44) is rendkívül magas. A megfelelő diagnosis és kezelés elősegítése céljából DE-CT használata javasolt azoknál a betegeknél ahol discoligamentáris sérülésre gyanakszunk, evvel kapcsolatban kialakítottunk egy kezelési algoritmust a légi sportban elszenvedett sérülésekhez.

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10. Bibliography of the candidate‘s publications

1. Related to the thesis

1. Backer HC, Vosseller JT, Deml MC, Perka C, Putzier M. (2021) Spinopelvic Dissociation: A Systematic Review and Meta-analysis. J Am Acad Orthop Surg, 29: e198-e207.
2. Backer HC, Wu CH, Vosseller JT, Exadaktylos AK, Benneker L, Krause F, Hoppe S, Albers CE. (2020) Spinopelvic dissociation in patients suffering injuries from airborne sports. Eur Spine J, 29: 2513-2520.
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