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Current Best Practices and Emerging Approaches in the Management of Acute Spinal Trauma

Lead Guest Editor: Kivanc Atesok
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Editorial

Current Best Practices and Emerging Approaches in the Management of Acute Spinal Trauma

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The past few decades have seen tremendous developments in surgeons' approaches to patients with acute traumatic injuries involving the spinal column and the spinal cord. As a result of advances in the scientific knowledge of the biomechanical and neurological bases of spinal trauma, along with ever-improved imaging modalities and operating techniques, nonsurgical and surgical management approaches to spine trauma patients have evolved. Due to its unique, diverse, and also challenging aspects, spinal trauma must be handled by orthopaedic surgeons and neurosurgeons with subspecialty training or particular expertise in spine surgery.

This special issue presents articles focusing on current concepts in the management of acute traumatic spinal injuries. These papers cover a broad range of spine trauma topics. A brief synopsis of the papers is as follows.

In a remarkable study of 6,370 patients with C2 fractures from the Swedish National Registry, A.-L. Robinson et al. underline the dynamic changes in the epidemiology of axis fractures that may result from changing population demographics, such as increasing age and level of activity. K. Atesok et al. critically evaluate the available evidence regarding posttraumatic spinal-cord injury without radiographic abnormality (SCIWORA). These expert authors have provided the most up-to-date algorithm for the management of patients with SCIWORA.

Whiplash is the most common injury associated with motor-vehicle accidents, affecting up to 83% of patients involved in collisions and imposing an overall economic burden of $3.9 billion annually in the US [1]. In light of the impact of whiplash on human health and healthcare systems, N. Tanaka et al. performed a literature review that points out the need for more comprehensive guidelines for addressing the diversity of the syndrome.

One of the pressing issues in the surgical treatment of fresh osteoporotic fractures with vertebroplasty or balloon kyphoplasty is the challenge of using cement that does not osteointegrate and is also associated with complications such as leakage, embolus, and a high setting temperature. P. Korovessis et al. compare the use of polymethacrylate with that of strontium hydroxyapatite (Sr-HA) in patients with single fresh AO-type A2 or A3 thoracolumbar vertebral body fractures who underwent vertebroplasty with PEEK plus short-segment percutaneous pedicle-screw fixation. The authors observed resorption and replacement of Sr-HA with vertebral bone at 12 months after surgery in all the patients treated with Sr-HA.

Traumatic lumbosacral dislocation is a severe, high-energy injury that usually requires surgical treatment. A. S. Moon et al. contribute a literature review summarizing lumbosacral dislocation with regard to the relevant prognosis, management, anatomy, classification schemes, clinical evaluation, and biomechanics of injury. In another interesting research paper on the same topic, Pearson and colleagues compare the outcomes of percutaneous fixation using indirect reduction techniques with open reduction and internal fixation in patients with spinopelvic dissociation.

Their results show no significant differences between the two techniques in terms of postoperative spinopelvic radiographic parameters.

Denis zone III sacral fractures involve the spinal canal and are associated with the highest prevalence and severity of neurological injury [2]. Surgical treatment of this fracture type with posterior open-plate fixation and other spinal instrumentation may cause soft-tissue damage and lead to wound complications. H. Irifune et al. join this special issue with a research paper reporting the clinical results of closed reduction in a hyperextended supine position with percutaneous transsacral-transiliac and iliosacral screw-fixation methods in patients with Denis zone III sacral fractures.

Finally, every spine surgeon practicing at a major level-1 trauma center needs to be knowledgeable in the management of gunshot wounds to the spine. Despite the severity and increasing frequency of spinal gunshot injuries, there is little agreement on the universal classification and management of these injuries. Realizing this, the editors of the special issue are pleased to present a fascinating article from J. R. Staggers et al. that critically assesses the utility of trauma-classification systems in such injuries. In their clinical research study, the authors investigated the validity of trauma-classification systems—including the Thoracolumbar Injury Classification and Severity Score (TLICS), Subaxial Cervical Spine Injury Classification and Severity Score (SLIC), and Denis's three-column model—when applied to spinal penetrating trauma from gunshots while secondarily evaluating the stability of these injuries.

Conflicts of Interest

Yohan Robinson is paid lecturer for DePuy Synthes and Medtronic and board member of CSRS Europe and AOSpine Nordic Region. Jason Pittman has some consulting with DePuy Synthes. The are no conflicts with regard to this issue. Steven Theiss has received payments for consulting from Ulrich and K2M. I also received research funding from Pfizer and Hensler.

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We would like to thank all the authors, reviewers, and editors who contributed their time and effort to this work, and we hope that our readers will find the contents of this special issue valuable and inspiring. This special issue is dedicated to my nephews Ayhan Atesok and Eli Rutkovsky, and my nieces Fahrunnisa Ok and Sezen Ok.

Kivanc Atesok
Nobuhiro Tanaka
Yohan Robinson
Jason Pittman
Steven Theiss

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Review Article

Traumatic Lumbosacral Dislocation: Current Concepts in Diagnosis and Management

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Traumatic lumbosacral dislocation is a rare, high-energy mechanism injury characterized by displacement of the fifth lumbar vertebra in relation to the sacrum. Due to the violent trauma typically associated with this lesion, there are often severe, coexisting injuries. High-quality radiographic studies, in addition to appropriate utilization of CT scan and MRI, are essential for proper evaluation and diagnosis. Although reports in the literature include nonoperative and operative management, most authors advocate for surgical treatment with open reduction and decompression with instrumentation and fusion. Despite advances in early diagnosis and management, this injury type is associated with significant morbidity and mortality, and long-term patient outcomes remain unclear.

1. Introduction

Traumatic lumbosacral dislocation is a rare clinical entity, characterized by unilateral or bilateral facet dislocations causing displacement at the level of the fifth lumbar vertebra in relation to the sacrum [1]. This injury pattern is caused by high-energy mechanisms such as motor vehicle collisions, falls from height, and crush injuries and is frequently associated with severe concomitant injuries [2].

There is some discrepancy in the literature with regard to the terminology describing injuries in this region; traumatic L5-S1 spondylolisthesis [3–7], lumbosacral/lumbopelvic dissociation [8–12], suicide jumper's fracture [13], spinopelvic dissociation [14–17], and spondylopelvic dissociation [18–20] have all been used to describe a spectrum of similar injuries. The terms spinopelvic and spondylopelvic dissociation are generally reserved for a more severe injury pattern with U-type, H-type, II-type, Y-type, or lambda type sacral fractures in conjunction with bilateral sacral fracture dislocations [17]. In this injury pattern, the spine and upper sacrum displace into the pelvis, separating from the remainder of the intact pelvic ring. However, to be a true lumbosacral dislocation, there must be dislocation of the facet joints between the fifth lumbar vertebrae and the sacrum.

Sacral fractures and lumbosacral dislocations are estimated to account for 1% of spinal fractures [21]. Current literature on lumbosacral dislocations is sparse, mainly consisting of case reports and small case series. The aim of this present study was to review the current literature on lumbosacral dislocation with regard to the relevant anatomy, biomechanics of injury, classification schemes, clinical evaluation, management, and prognosis.

2. Anatomy and Biomechanics of Injury

The lumbosacral junction consists of the L5 and S1 vertebra, as well as the corresponding intervertebral discs and apophyseal joints. It is a well-supported region stabilized by the local paraspinous musculature and iliolumbar ligamentous complex, which connects the transverse processes of L5 to the posterior iliac wing and crest. The ligamentous structures contributing to iliolumbosacral stability include the supraspinous ligament, ligamentum flavum, interspinous ligament, iliolumbar ligament, lateral lumbosacral ligament, and the facet joint capsule. The lumbosacral joint has an increased inclination in the sagittal plane and the facets at this junction have a more vertical, frontal plane orientation [22], resisting anterior translation and making dislocation a

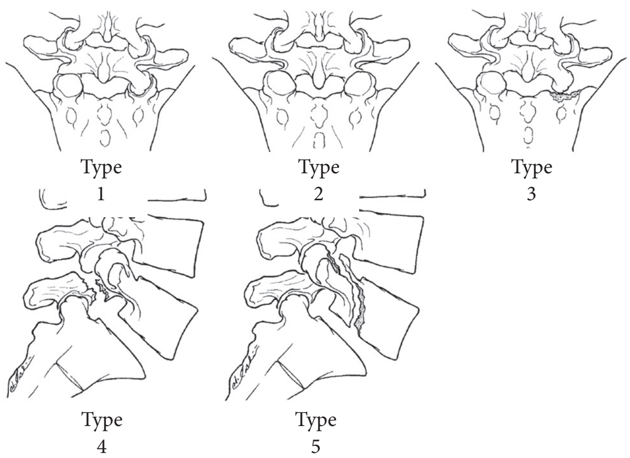

Figure 1: Classification of fracture-dislocation of the fifth lumbar vertebra according to Aihara et al. [1].

rare injury. Several authors have suggested that preexisting spondylolysis at the level of L5 may be a predisposing factor for the disruption of the lumbosacral junction with additional trauma [23–27].

This injury pattern is considered an unstable injury with disruption of virtually all stabilizing structures in that area, and may be suspected in cases where impact occurs cranial to or directly at the level of L5-S1. The direction of dislocation may vary depending on the traumatic force vector, and includes anterior, anterolateral, lateral, and posterior dislocations. Anterior dislocations, resulting in L5 anterior to S1, are most common [3, 23], while posterior dislocations are typically associated with more severe neurological injuries [3, 28–31].

Watson-Jones first described this injury pattern in 1940, and suggested forced hyperextension as the mechanism of injury [32]. However, Roaf et al. in 1960 demonstrated experimentally that the forces responsible for anterior dislocation were a combination of hyperflexion, axial rotation, and compression [33]. To date, the literature has shown hyperflexion to be the most common mechanism of injury [23]. However, isolated hyperflexion is unlikely to produce this type of injury in the lumbar spine [33]. Other contributing forces may include compression [6, 7, 34, 35], rotation [36–42], distraction [43, 44], translation [45–47], lateral translation [48–50], lateral bending [25, 36, 51], and direct traumatic vectors [44, 52].

Each variant of a lumbosacral dislocation is thought to occur through a slightly different combination of forces [7, 25, 28–32, 49, 53–56], and while multiple mechanisms have been postulated, no biomechanical study directly supporting a given mechanism of injury has been performed.

3. Classification

In 1998, Aihara et al. proposed a classification scheme specifically for fracture dislocations of the fifth lumbar vertebra based on the existing literature (Figure 1) [1]. Type 1 involved unilateral lumbosacral facet dislocation with or without facet fracture, with an intact contralateral facet. Type 2 involved bilateral lumbosacral facet dislocation with or without facet fracture. Type 3 involved unilateral lumbosacral facet dislocation and contralateral lumbosacral facet fracture. Type 4 involved dislocation of the body of L5 with bilateral fracture of the pars interarticularis (acute spondylolytic spondylolisthesis). Type 5 involved dislocation of the body of L5 with fracture of the body and/or pedicle with or without injury of the lamina and/or facet. This first attempt at a classification scheme did not distinguish between intact and unilateral/bilateral fractured facets, and other classification schemes based on varying anatomic factors exist in the literature [57, 58].

4. Clinical Evaluation

Given the substantial, high-energy trauma necessary for this injury, there are typically a variety of associated injuries involving bony, ligamentous, soft tissue and/or neurovascular elements [21], and the diagnosis may be easily overlooked on initial evaluation. Shen et al. reported that 10% of reported lumbosacral fracture dislocations were not initially recognized, though these were in patients where X-ray was the primary imaging modality [36]. Clinical presentation varies widely, [59–78] and may include severe lower back pain with exam findings such as flank hematomas, abrasions or palpable step-offs of the spinous processes.

Associated injuries are likely to occur locally, but may also involve other body cavities such as the abdomen, pelvis, thorax, and cranial cavity [21, 79]. Bony injuries may include vertebral fractures of the transverse processes, spinous processes, and sacral promontory, as well as distant fractures such as in the ribcage or femur [36]. Local soft tissue involvement includes the supraspinous ligaments, paraspinous musculature, facet joint capsules, dura and intervertebral disc [80, 81].

Typically associated neurological injuries include cauda equina syndrome and disruption of the lumbosacral plexus [36, 46, 82, 83]. Neurologic findings on exam may include hypoesthesia of the lower extremities, radiculopathy, bowel dysfunction, and urinary retention [84]. S1 is the most frequently affected nerve root [22, 39, 44, 49, 85], and more serious neurological injuries include paraplegia, although this is rare [81]. Neurologic compromise, as well as persistent neurologic deficits postoperatively, is more likely in bilateral dislocations or dislocations with fractures [25, 35, 58, 71, 72, 86].

There is a wide range of reported rates of neurological injury in the literature. Aihara et al. reported a 68.4% rate of neurologic deficit in 57 cases [1], while only 3 out of 11 patients (27.3%) in the series by Vialle et al. demonstrated neurological injury [58]. Grivas et al. reported a 58% rate of neurologic deficit for all lumbosacral fracture dislocations [2], while Arandi et al. found an 89% rate of neurological injury for complete lumbosacral dislocations [59].

5. Imaging

Initial work-up with high-quality standard radiographic studies will demonstrate an abnormal relationship between the lumbosacral facets. Clues to this pathology on the anteroposterior view include transverse process fractures (sentinel fractures), obliquity of L5 on sacrum, widening of the paravertebral soft tissue lines, widening of the interpedicular distance, and rotational deformity of the spinous processes [22, 27, 36, 85, 87]. On the lateral view, there may be an increased interspinous distance, kyphosis of L5 on S1, anterior or posterior subluxation of L5 on S1, anterior narrowing of height of disc space, disrupted spinolaminar lines, or amplification of lumbar lordosis [22, 27, 36, 87].

Advanced imaging modalities are now routinely used in virtually all high-energy trauma patients and will readily demonstrate the injury (Figure 2). A computed tomography (CT) study allows for visualization of injuries to the posterior elements and locked or fractured facet dislocations with displacement of L5 on S1 [22, 62, 88]. CT may show associated fractures, such as laminar or sacral fractures, as well as a "naked facet sign" on the axial plane, due to the L5 facets passing superiorly over the facets of S1 [22, 63, 87, 89, 90]. This gives the CT scan an image of empty or perched facets, and is indicative of facet dislocation. A magnetic resonance imaging (MRI) study will also demonstrate the dislocation, along with other local injuries including disc herniation, dural tears, torn discs, root compression, and degree of musculoligamentous injury. MRI can be instrumental in localizing sites of neural compression [22, 62, 87].

6. Management

Initial management includes appropriate evaluation, stabilization and resuscitation measures according to standard Advanced Trauma Life Support (ATLS) protocol, and emergent injuries should be treated first in order of priority [91]. There are a few published experiences with nonoperative management with techniques including closed reduction, traction and immobilization [26, 49, 56, 77, 92–95]. To the authors' knowledge, the last case report of an adult treated conservatively was published in 2000, with the authors opting for conservative treatment due to the patient's delayed presentation of three months [92].

In the pediatric population, nonsurgical treatment remains a consideration with any spinal condition due to concerns of disproportional growth of the anterior spine after isolated posterior fusion resulting in a progressive, iatrogenic deformity frequently referred to as the "crankshaft phenomenon." [96] However, with closed reduction and immobilization, studies have documented risk of secondary neurological injury during external reduction maneuvers [46, 56, 58, 93]. In addition, prior reports have documented an increased risk of progressive back pain, deformity, and neurologic deterioration with conservative treatment [4, 26, 31].

Acute lumbosacral dislocations are unstable, and a growing body of literature recommends early surgical reduction with instrumentation [1, 59, 71, 81, 92, 97, 98]. Historic techniques for instrumentation have included a wide range of constructs including interspinous screws, posterior articular screws, sublaminar wiring, Harrington hooks and rods, and osteosynthesis with posterior plates or with

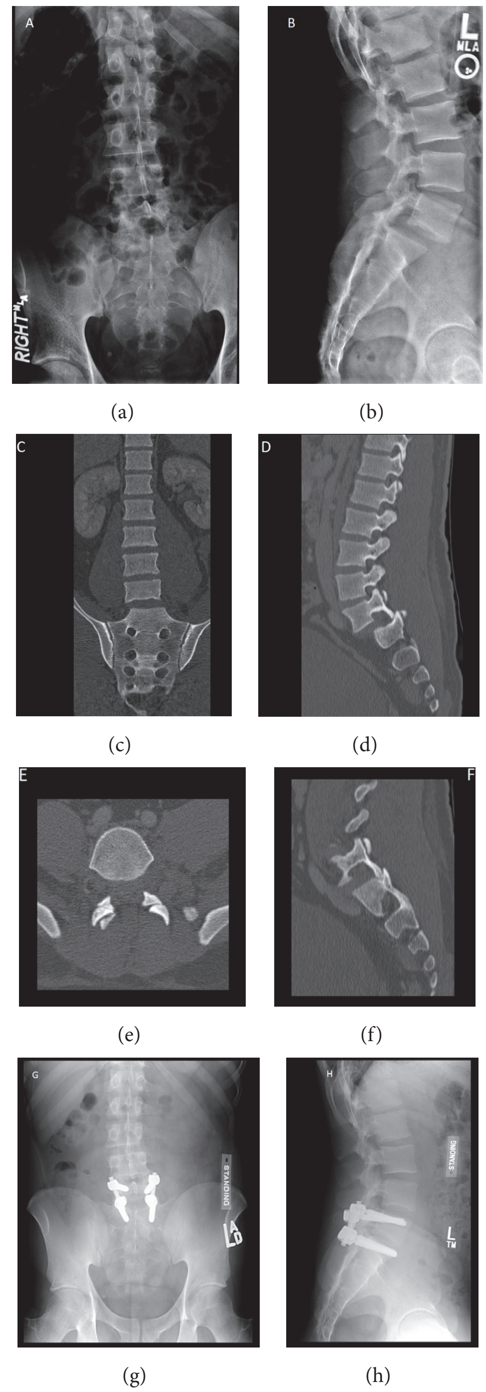

Figure 2: Imaging of a 25-year-old male patient who was involved in an all-terrain vehicle accident. He was ejected from the vehicle and presented with low back pain and intermittent bilateral lower extremity radicular pain with paresthesia. Figures (a) and (b) demonstrate anteroposterior and lateral radiographs, respectively. Coronal CT shows minimal lateralization of L5 over S1 (c). Sagittal view shows anterior dislocation of L5 over S1 with jumped facets (d). Axial (e) image cut through the same level as the sagittal image (f) shows bilateral jumped facets at L5-S1. The patient underwent posterior spinal instrumentation and fusion of the L5 and S1 vertebrae using pedicle screws and rods. Postoperative anteroposterior (g) and lateral (h) images demonstrate a reduced L5-S1 joint. (Courtesy of University of Alabama at Birmingham, Department of Orthopaedic Surgery, Spine Fellowship Program, Birmingham, Alabama, USA).

Cotrel-Dubousset-type instrumentation [23, 25, 27, 30, 40, 54, 64, 84, 99–104].

Currently, treatment should consist of pedicle screws in L5 and S1, assuming the pedicles at these levels are intact. While this short segment construct may be sufficient in patients with good facet apposition following reduction, fixation may need to be extended proximally to L4 or distally to the pelvis when bony support is poor after reduction. The lumbosacral canal should be examined intraoperatively for any bone or disc fragments, if MRI indicates neurocompression [3, 54, 58]. Spinal cord monitoring can be used to confirm intact peripheral nerve function during reduction maneuvers and significant distraction should be avoided during reduction.

All dislocation injuries should also be treated with fusion. While there is little literature describing the superiority of one fusion method over another, options include posterior arthrodesis [1, 59], circumferential arthrodesis [27, 70, 72], and interbody fusion, which is often used in cases of significant disc disruption [24, 64, 99]. Partial facetectomy may be performed in patients with traumatic lumbosacral dislocation to facilitate reduction [34, 46, 70, 85, 99], although intact apophyseal joints are preferred to prevent redislocation [34].

Numerous case reports support decompression in patients with evidence of neurologic compromise [1, 59, 71, 81, 92, 97, 98]. The authors of the current study suggest surgical decompression is patient-dependent, and recommend selective decompression based on the patient's clinical exam and sites of neurologic compression as evidenced on MRI. In cases of cauda equina syndrome or delayed reduction, decompressive laminectomy may be performed [40, 43, 70, 83]. However, this may lead to increased instability and is not indicated in the absence of neurologic compromise [68, 77, 85].

7. Prognosis and Complications

Although there have been a few reports of satisfactory outcomes after nonoperative management [56, 92, 93], many patients initially treated conservatively eventually required fusion due to progression of listhesis and/or neurological deficit [5–7, 22, 40, 51, 54]. However, even with surgical intervention there may be residual disability and permanent neurological dysfunction [1, 98, 100–103]. The degree of residual translational displacement and kyphosis postoperatively may be associated with clinical outcomes following surgery. Perioperative surgical complications include infection and wound dehiscence, not unlike other surgeries in this region. Additional complications include mechanical issues such as instrumentation failure that can occur late, requiring reoperation years after the initial surgery [68, 92, 102]. Adelved et al. published long-term results in a small series of patients with traumatic lumbosacral dissociation, showing that functional impairments, pain, and poor patient-reported health were common, along with high rates of neurologic, urinary, and sexual dysfunction [8]. Conversely, De lure et al. demonstrated successful long-term clinical outcomes in a small cohort of patients who underwent lumboiliac fixation for lumbosacral dislocation injuries [92]. Long-term prognosis is unclear due to the small number of reported cases with limited follow-up and heterogeneous results.

8. Summary

Traumatic lumbosacral dislocation is a rare injury pattern resulting from high-energy trauma. It often presents with multiple concomitant injuries, and may be easily overlooked on initial evaluation. Acute complete dislocations are highly unstable, three-column injury patterns, requiring surgical intervention with open reduction and internal fixation. Early diagnosis and treatment are likely to improve clinical outcomes. Despite advances in diagnosis and management, these injuries are associated with significant morbidity and mortality.

Conflicts of Interest

The authors have no conflicts to declare.

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Research Article

Stability of the Subaxial Spine after Penetrating Trauma: Do Classification Systems Apply?

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Objective. Blunt spinal trauma classification systems are well established and provide reliable treatment algorithms. To date, stability of the spine after civilian gunshot wounds (CGSWS) is poorly understood. Herein, we investigate the validity of trauma classification systems including the Thoracolumbar Injury Classification and Severity Score (TLICS), Subaxial Cervical Spine Injury Classification and Severity Score (SLIC), and Denis' three-column model when applied to spinal penetrating trauma from gunshots, while secondarily evaluating stability of these injuries. *Methods*. Gunshot injuries to the spine were identified from an institutional database from ICD-nine codes. Trauma scorings systems were applied using traditional criteria. Neurologic compromise and spinal stability were evaluated using follow-up clinic notes and radiographs. *Results*. Thirty-one patients with CSGSW were evaluated. There was an equal distribution of injuries amongst the spinal levels and spinal columns. Twenty patients had neurological deficits at presentation. Eight patient had a TLICS score >4. Three patients had a SLIC score >4. One patient had surgical treatment. Nonoperative treatment did not lead to spinal instability or adverse outcomes in any cases. The posterior column had a high correlation with neurologic compromise, though not statistically significant (p=.118). *Conclusions*. The TLICS, SLIC, and three-column classification systems cannot be applied to CSGSW to quantify injury severity, predict outcomes, or guide treatment decision-making. Despite significant neurologic injuries and disruption of multiple spinal columns, CSGSW do not appear to result in unstable injuries requiring operative intervention. Further research is needed to identify the rare spinal gunshot injury that would benefit from immediate surgical intervention.

1. Introduction

Civilian spinal gunshot wounds (CSGSW) are an increasingly common injury and carry significant morbidity and mortality [1–4]. Annually, CSGWS are the third most common cause of spinal injury and account for approximately 13-17% of all traumatic spinal injuries [1, 2, 5–9]. Despite the severity and frequency of CSGSW, there is little agreement on the universal classification and management of these injuries since surgeons continue to treat patients based on institutional, geographical, and surgeon preference [10–12]. As a result, numerous classification systems and stability concepts have been applied to these injuries in an attempt to improve care and optimize outcomes.

Three of the more popular spinal classification systems are the Thoracolumbar Injury Classification and Severity Score (TLICS), Subaxial Cervical Spine Injury Classification and Severity Score (SLIC), and Denis' three-column model. TLICS was introduced in 2005 and is a point-based system that utilizes the morphology of the injury, integrity of the posterior ligamentous complex (PLC) and neurologic status to evaluate an injury [10]. SLIC is another point-based system that was introduced in 2007 and is based on injury morphology, integrity of the disco-ligamentous complex, and neurologic status [13–15]. Both TLICS and SLIC give an injury score that correlates with injury severity, allowing the provider to quantify injury severity and guide treatment [13–15]. Denis' three-column model was introduced in 1983 and is based on radiographic findings [16, 17]. It divides the spine into three anatomic columns and defines instability as disruption of 2 or more columns [16, 17]. Although the three-column system provides an intuitive nomenclature for describing spinal injuries, it does not provide prognostic information or guide clinical decision-making [10].

These systems have been validated in many studies as reliable and reproducible for blunt force trauma; however, to date their use in penetrating trauma has not been validated [4, 10, 13–15]. Currently there are no spinal classification systems that were designed for penetrating trauma, and data in the literature is limited. This study seeks to assess the utility and legitimacy of the TLICS, SLIC, and three-column classification systems to quantify injury severity, predict outcomes, and guide treatment decision-making for CSGWS, while secondarily evaluating stability of these injuries.

2. Materials and Methods

After institutional review board (IRB) approval was obtained, we conducted a retrospective cohort review of patients who sustained low-velocity gunshot injuries to the spine from 2003-2016 using ICD-nine codes. Patients were treated by orthopedic and neurologic surgeons from a single level-one trauma center. All treatments were non-randomized and were at the discretions of the treating surgeon. Inclusion criteria included gunshot injuries that involved any aspect of the cervical, thoracic, lumbar, or sacral spine. Single and multiple gunshot injuries were included. Patients with non-spinal gunshot injuries were included as long as the injuries did not affect management of their spinal injuries. Patients who were unable to provide neurological exam due to clinical condition or with less than one month of follow up were excluded from the study. Also, patients without computed tomography (CT) imaging on the date of injury or radiographic or CT imaging at final follow up were excluded.

Standard patient demographic information was reviewed, including: age, date of injury, fracture morphology, fracture level, treatment, neurologic status, and final follow up data. Neurologic status was assessed using the American Spine Injury Association (ASIA) classification [18]. In some instances, a single ballistic injury resulted in multiple spinal level injuries due to an oblique sagittal tract. For these patients and for those with multiple spinal gunshot injuries, all spinal levels and columns involved were counted, but only the most severe injury was used for neurological and classification analysis. Initial CT evaluation was performed to assess fracture morphology, injury level, and coronal and sagittal alignment. The three-column system of spine stability was applied as classically described by Denis [16]. The Subaxial Cervical Spine Injury Classification and Severity Score (SLIC) and Thoracolumbar Injury Classification and Severity Score (TLICS) were calculated based off original papers by Vaccaro [10, 13]. In order to classify complex fracture patterns according to the pre-defined morphologic patterns of SLIC and TLICS systems, fractures that only affected the anterior column of the vertebral body were described as compression fractures and were assigned one point. Fractures that involved the anterior and middle columns were described as burst fractures and assigned two points. Injuries that involved the vertebral body and the posterior elements were assigned four points. Isolated posterior column injuries were given a morphologic score of zero. Patients with intact posterior elements were given no points whereas injuries that caused complete destruction of the posterior elements were classified as having a suspected PLC injury and given two points. On final follow-up, radiographs were evaluated for sagittal, coronal, and axial spinal alignment and final neurologic status was recorded.

Demographic information was evaluated using descriptive statistical analysis. Further statistical analysis was done using chi-squared tests. A $p < 0.05$ was considered statistically significant.

Table 1: Demographic and injury data.

	Mean	SD
Age (yrs)	34.0	14.8
	Number	**% of Patients**
Sex		
Male	27	87.1
Female	4	12.9
Spinal Levels Involved		
Cervical	8	25.8
Thoracic	14	45.2
Lumbar	13	41.9
Sacral	1	3.2
Neurologic Grade		
ASIA A	9	28.0
ASIA B	2	6.0
ASIA C	3	9.0
ASIA D	6	19
ASIA E	11	34.0
Treatment		
Surgery	1	3.2
Nonoperative	30	96.8
Stability		
Stable	31	100.0
Unstable	0	0.0

3. Results

Thirty-one patients (27 males, 4 females) with 33 spinal gunshot injuries met the inclusion criteria for the study. Mean age was 34.0+/- 14.8 years (range 17-63 years) with an average follow up of 2.0 +/- 2.6 years (range 1-99 months). Demographic, fracture, and neurologic information is shown in Table 1. ASIA neurological status was recorded in all patients with 20 of the 31 patients (64.5%) having neurologic deficits (ASIA A-D) and 11 patients without any neurologic deficits (ASIA E) immediately after presentation. Complete spinal cord injury (ASIA A) was the most commonly encountered deficit (9 patients). There was a nearly equal representation of CSGSW among cervical, thoracic, and lumbar regions, but

Table 2: TLICS Score.

	Thoracic Spine	Lumbar Spine	Total
TLICS Score 0-3	4	7	11
TLICS Score 4	3	1	4
TLICS Score >4	4	4	8

Table 3: SLIC Scores.

	Cervical Spine
SLIC Score 0-3	5
SLIC Score 4	0
SLIC Score >4	3

Table 4: Denis Classification.

	Number	%
Number of Columns Involved		
1 Column	12	38.7
2 Columns	9	29.0
3 Columns	10	32.2
Column Injuries		
Anterior	20	52.6
Middle	18	47.4
Posterior	20	52.6
Columns Involved		
Anterior only	3	7.9
Middle only	0	0.0
Posterior only	9	23.7
Anterior/Middle	11	28.9
Posterior/Middle	1	2.6
Anterior/Middle/Posterior	10	26.3

only one injury that involved the sacral spine. Twenty-one patients (67.7%) had injuries involving multiple vertebrae. Two patients (6.5%) had isolated intervertebral disk involvement. All but one patient were treated nonoperatively.

On follow up, no patients displayed significant change in spinal alignment or neurologic status. One patient with concomitant bowel injury developed spondylodiscitis and a progressive lumbar kyphosis secondary to near complete vertebral body collapse. This patient's CGSW injury was isolated to the posterior elements and their deformity was deemed unrelated to instability secondary to the initial trauma.

3.1. Thoracolumbar Injury Classification and Severity Score (TLICS). TLICS scores for each patient with thoracolumbar involvement are summarized in Table 2. Eleven patients of the 23 patients with thoracolumbar injuries (47.8%) had a TLICS score of 0-3 suggesting conservative therapy. Four patients (17.4%) scored a 4 suggesting that surgery is up to the surgeon's discretion. Eight patients (34.8%) had a TLICS score of greater than 4 suggesting surgical stabilization is appropriate. Despite the high number of patients for whom surgery is indicated according to TLICS, none had surgery.

3.2. The Subaxial Cervical Spine Injury Classification and Severity Score (SLIC). SLIC scores for each patient with cervical spine involvement are summarized in Table 3. Five of the 8 patients with cervical injuries (62.5%) had a SLIC score of 0-3, suggesting conservative therapy. Three patients (37.5%) scored greater than 4, suggesting surgical stabilization is appropriate. Only 1 patient (12.5%) with a SLIC score of 5 had surgical stabilization.

3.3. Denis' Three-Column Model. Table 4 summarizes the number of injuries per column as it pertains to Denis' three-column model. There was a near equal distribution of one-column (12), two-column (9), and three-column (10) injuries, as well as a near equal involvement of anterior (20), middle (18), and posterior columns (20). The association between column involvement and neurologic injury is described in Figures 1 and 2. One and two-column injuries involving the anterior and middle columns had a low correlation with neurological involvement. Though it was not statistically significant, there was a high correlation of the posterior column with neurologic involvement (p =0.118). Of note, three-column injuries also had a high correlation with neurological involvement.

4. Discussion

Contemporary understanding of spinal injuries and their optimal management is continuously evolving. Classification systems have been used for decades for spinal trauma as a helpful resource, but there is little agreement on the universal classification across a broad spectrum of injuries. The TLICS, SLIC, and the three-column classifications have been validated in blunt trauma and provide useful information on the mechanical stability of the spine [4, 10, 13–15]. The current study investigated the utility of trauma classification systems in penetrating gunshot injuries, a topic that has yet to be discussed.

Ideally, a classification system should be able to provide prognostic information and help guide treatment. Application of TLICS and SLICS scores system were not able to predict injury severity or instability in our study. Eight patients (34.8%) with thoracolumbar injuries and 3 patients (37.5%) with cervical injuries had a TLICS or SLIC severity score that equated with recommendation for surgery. All but one of these patients were successfully managed conservatively with the one exception undergoing early surgical stabilization.

Fracture morphology was a major limiting factor for the general utility of TLICS and SLIC systems since penetrating

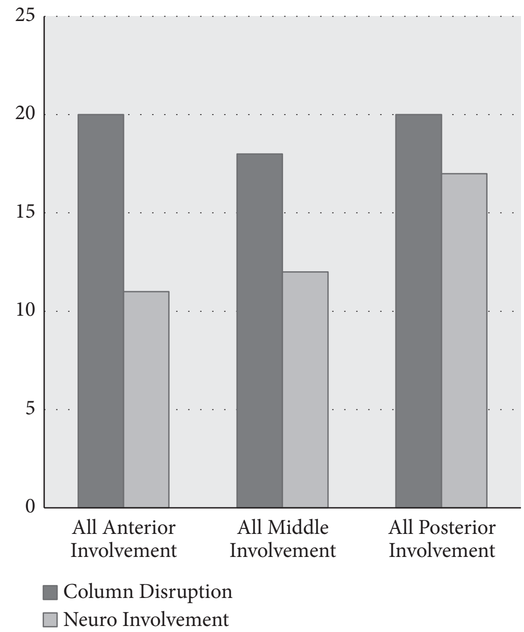

Figure 1: Correlation of neurologic injury and column disruption in Denis' three column stability system.

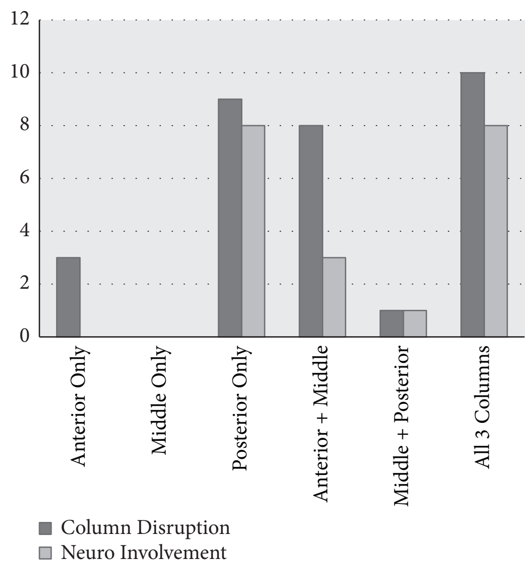

Figure 2: Correlation of neurologic injury and column disruption in Denis' three column stability system.

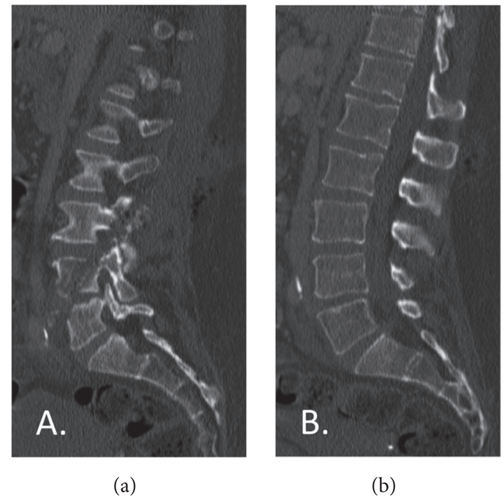

Figure 3: (a) Parasagittal image demonstrating bullet tract involving multiple vertebral bodies and articulating facets joints. (b) Midsagittal image on the same patient seen in image 2A showing intact alignment despite CSGSW.

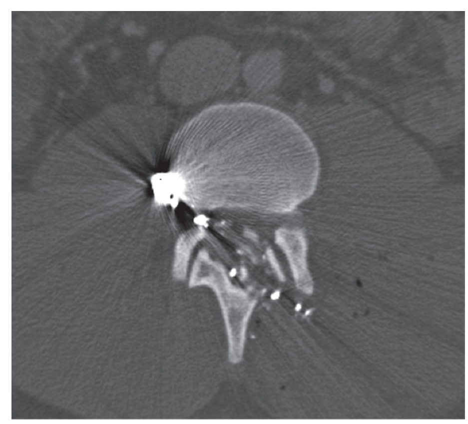

Figure 4: Bullet seen traversing spinal canal in a patient with complete neurologic injury (ASIA A).

wounds do not usually result in classic fracture patterns. By definition, burst and compression fractures result in a loss of vertebral body height. In our cohort, nearly all of the CSGSW retained normal vertebral body alignment, intuitively making them more stable than their nomenclature suggested (Figure 3). This increased stability is thought to be the result of nearby supporting structures that are more likely to be maintained in penetrating trauma.

In TLICS and SLIC, neurologic status is used as a critical indicator of stability, but this may not have the same utility in CSGSW as it does in blunt force trauma. In our study, roughly two-thirds of patients had neurologic involvement without any patients showing spinal instability. This data is consistent with previous work by Bumpass et al. who showed a high rate of neurologic compromise despite low rates of biomechanical instability with CSGSW [19]. Prior studies suggest that in CSGSW, neural and spinal cord damage are generally due to direct impact, thermal energy, or blast effect (Figure 4) rather than compression or tension as seen in blunt force trauma [1, 20].

The Denis three-column spinal stability model provided no insight into instability or prognostic information for CSGSWS. Ten patients (32.2%) sustained three-column injuries as classified by Denis but all were successfully treated without surgical treatment. Though the posterior column had a high correlation with neurologic damage, this is believed to be related to classification system's basis on anatomy and the location of the spinal cord.

Our data is consistent with past studies supporting the inherit stability of the spine after CSGSW [2, 19, 21–23]. The authors of the current study find no value in classifying penetrating injuries with conventional spinal classification systems as they provide no appreciated information on mechanical stability. As previous studies have shown surgery frequently correlates with an increase in complications without improvement in outcome [19], the role of surgery should be limited to the rare patient with overt mechanical instability.

Our study is not without limitation, including its retrospective study design with a limited number of patients. Additionally, by design our study evaluates three spine trauma classification systems that were specifically designed for blunt force trauma in the setting of penetrating trauma. Though this provides little novel information, our study closes the literature gap on this topic and confirms current practices relating to penetrating trauma of the spine. A small number of patients were lost to follow-up and neurological exam required data extraction from numerous outpatient charts that were at times incomplete. Additionally, bullet fragments on CT scan serve a potential source of error as they proved to be a challenge in assess fracture morphology secondary to artifact.

5. Conclusion

We conclude that the TLICS, SLIC, and three-column classification systems cannot be applied to CSGSW to quantify injury severity, predict outcomes, or guide treatment decision-making. Despite significant neurologic injuries and disruption of multiple spinal columns, CSGSW do not appear to result in unstable injuries requiring immediate surgical stabilization. TLICS and SLIC grossly over-indicate surgery for many patients that actually did well when treated conservatively. Our data suggests that refraining from operative treatment does not result in worse outcomes; therefore, we propose that CSGSW warrant a trial of nonoperative management after injury. Further research is suggested to find the rare injury that would benefit from immediate surgical stabilization or debridement.

Data Availability

All results and conclusions of the current study can be explained through the tables published and referenced in the manuscript. The authors decline publishing raw data in order to protect patient information.

Disclosure

This research was presented at the Global Spine Congress 2015 in Buenos Aires, Argentina (podium presentation). Level of evidence is retrospective review, level 4.

Conflicts of Interest

The authors declare that there were no conflicts of interest in conducting this study.

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Research Article

Closed Reduction in a "Hyperextended Supine Position" with Percutaneous Transsacral-Transiliac and Iliosacral Screw Fixation for Denis Zone III Sacral Fractures

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Background. Herein, we demonstrate the clinical results of closed reduction in a hyperextended supine position with transsacral-transiliac (TSTI) and iliosacral (IS) screw fixations for Denis zone III sacral fractures. *Patients and Methods*. Sixteen consecutive patients with Denis zone III sacral fractures who were treated between January 2009 and September 2016 were evaluated. All patients were treated using percutaneous TSTI/IS screw fixation during closed reduction performed with patients placed in a hyperextended supine position with body manipulation. The clinical and radiological results were evaluated, and the neurological outcomes were retrospectively assessed using Gibbon's classification system. The clinical outcomes were evaluated using the German Multicenter Study Group Pelvic Outcome Scale (POS). *Results*. The sacral kyphotic angle was reduced by $18.06^\circ \pm 15.26^\circ$ (mean kyphotic angle: pre-OP, $39.44^\circ \pm 20.56^\circ$; post-OP, $21.38^\circ \pm 7.39^\circ$), and fracture translation was reduced by 5.93 ± 4.95 mm (mean fracture translation: pre-OP, 8.69 ± 8.03 mm; post-OP 2.75 ± 3.97 mm). The mean initial Gibbon's score was 3.00 ± 1.32. Among 15 patients with a follow-up duration of over 12 months, the mean reduction loss in the sacral kyphotic angle was $5.87^\circ \pm 10.40^\circ$ and was 1.00 ± 3.00 mm for the fracture translation. The final Gibbon's score was 1.80 ± 1.21, and 73.3% of patients had good results based on the POS score. *Conclusions*. Although closed reduction in a hyperextended supine position with percutaneous posterior screw fixation is associated with some surgical limitations and technical difficulties, the procedure is minimally invasive and highly effective for stabilizing Denis zone III sacral fractures.

1. Introduction

Denis zone III sacral fractures are generally due to high-energy traumas such as falls from heights, traffic accidents, and crush injuries, with most of these fractures occurring in patients with polytrauma [1]. Zone III sacral fractures are relatively rare injuries, reportedly accounting for only 3–5% of all sacral fractures [2–4]. Importantly, these fractures are associated with a high rate of neurologic injury, including sensory and motor deficits in the lower legs; saddle anesthesia; and bowel, bladder, and sexual dysfunctions [2].

Historically, the standard treatment for Denis zone III sacral fractures did not involve surgery or was limited to sacral laminectomy [1, 5]. However, given the advances in internal fixation techniques, cases with minimal kyphosis and no neurological deficits can be treated using several commonly performed surgical procedures such as spinopelvic fixation [6], posterior plate fixation [7], and iliosacral screw fixation [8]. However, no clear guidelines currently exist regarding appropriate treatment strategies and indications for Denis zone III sacral fractures. Spinopelvic and posterior plate fixation have shown good reduction and neurological recovery but are associated with long operating times. Moreover, the surgery is performed in the prone position, which may be particularly disadvantageous for polytrauma patients.

In addition, the use of posterior plates and other spinal instrumentations may cause soft tissue damage and lead to wound complications. To minimize the risk of such complications, minimally invasive approaches have been increasingly used for these fractures. In recent reports, minimally invasive posterior screw fixations for pelvic ring fractures, including transsacral-transiliac (TSTI) and iliosacral (IS) screw fixations, have been reported to have a number of clinical and biomechanical advantages [9–13].

The purpose of the present study was to review our experiences and demonstrate the clinical results of closed reduction in a hyperextended supine position with percutaneous TSTI/IS screw fixation methods for Denis zone III sacral fractures.

2. Patients and Methods

Patients with Denis zone III sacral fractures classified as AO/OTA type C pelvic injuries, treated between January 2009 and September 2016, were selected from our trauma database. Patients who had undergone surgical treatment and had been followed up for a minimum of 12 months were selected for analysis. The patients' medical records were reviewed retrospectively, and the fractures were classified by the sacral level according to the method of Roy-Camille (as modified by Strange-Vognsen and Lebech) and the fracture morphology [1, 14, 15].

The following injury data were collected: demographics, mechanism of injury, associated injury, and the ISS. An initial clinical neurological examination was performed if the patient's condition permitted and was graded according to the classification system described by Gibbons et al [5, 16]. Preoperative imaging consisted of pelvic anterior-posterior radiographs and multislice CT scans. Collected postoperative data included the results from clinical and radiological assessments. Radiographic assessments of the sacral kyphotic angle, fracture translation, implant position, and decompression were performed using standard radiography of the pelvis and multislice CT [17, 18]. Additionally, multidisciplinary follow-up examinations were performed by an orthopedic surgeon (H.I.).

2.1. Reduction and Operative Techniques. During the 8-year study period, a standardized operative technique using closed reduction and posterior pelvic ring fixations (TSTI and/or IS screw fixation) was performed. In patients with combined sacral fractures and anterior pelvic ring injuries, staged and/or one-stage reconstruction was performed. Injuries of the anterior part of the pelvic ring were treated using an anterior extraperitoneal or percutaneous approach. Posterior pelvic ring fixation was performed through the percutaneous approach.

2.2. Operative Procedure. For posterior screw fixation, the patients were positioned supine on a radiolucent table and in hyperextension with handmade pillows placed vertical to the sacral fracture line (Figure 1(a)). Under fluoroscopic guidance, closed fracture reduction was performed. When the fracture reduction quality was insufficient, additional pillows were placed and/or manipulation of the patient's body was performed (Figure 1(b)). The manipulation maneuver involved putting a tow in the longitudinal direction while pushing the trunk and lower limbs to the table (Figure 1(c)). After closed reduction, percutaneous screw insertion was performed under fluoroscopic guidance (Figure 1(d)). In principle, two or more TSTI screws were inserted; when this was not possible, the TITS screws were set in combination with an IS screw. Screws utilized at our institute included 6.5 mm (diameter) cannulated cancellous screws provided by Depuy-Synthes, Inc. (partial thread; maximum length: 120 mm) and Meira, Inc. (partial and full thread; maximum length: 150 mm). Direct sacral decompression was not initially performed.

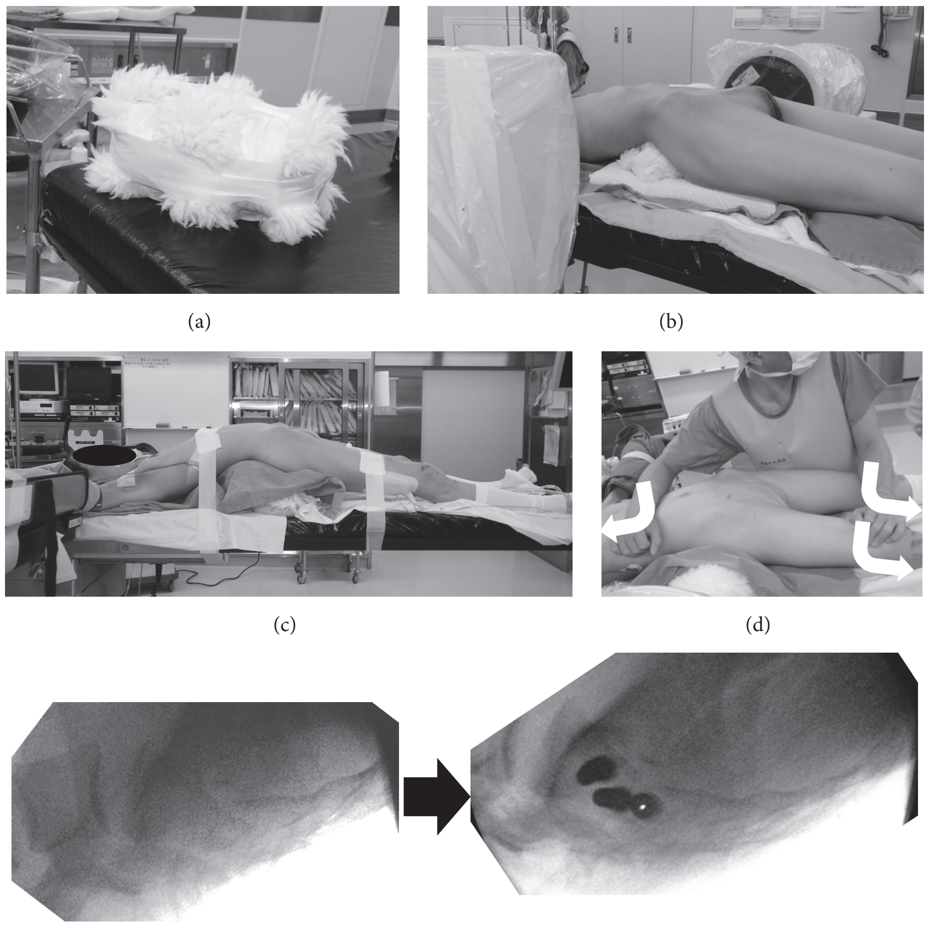
2.3. Postoperative Care. The patient was allowed to sit with the torso upright starting on postoperative day 1. Nonweight bearing activities were allowed 4 weeks after definitive surgery. Weight-bearing activities began 5 weeks after definitive surgery.

After definitive pelvic ring fixation, a follow-up CT was performed within 1 week to indirectly evaluate the decompression quality. If a remnant fracture fragment in the sacral canal and/or poor indirect decompression quality was found, a secondary direct sacral decompression was considered. One orthopedic trauma surgeon (H.I.) performed all operative procedures. Early and late complications associated with the surgical treatment were recorded.

2.4. Radiological Evaluation. The sacral kyphotic angulation of the Denis zone III sacral fracture was measured from sagittal CT reformations by measuring the angle between the posterior sacral cortices, superior and inferior to the level of the transverse fracture. Fracture translation was also measured from the sagittal CT reformations by measuring the displacement of the anterior cortex of the sacrum above and below the transverse fracture (Figure 2). All measurements involving the preoperative, postoperative, and final radiographs, as well as the CT images, were performed by the first author.

2.5. Outcome Evaluation. Lower extremity sensory and motor function and rectal examinations were performed pre- and postoperatively to identify injuries to the lower lumbosacral plexus. Neurological deficits from cauda equina injuries were classified according to the method of Gibbons et al [5]. Improvements in neurological function at the final follow-up were similarly assessed.

The clinical outcomes were evaluated at the final follow-up using the clinical criteria of the German Multicenter Study Group Pelvis Outcome Scale (POS) [19]. These clinical criteria (pain, functional impairment, persistent neurological and urological impairments, and bowel dysfunction) are based on the clinical results and range from 1 to 4 points; a POS score of 3–4 points is considered to be a good outcome, whereas a score of 1–2 points indicates a poor outcome.



(a) (b) (c) (d) (e)

Figure 1: Closed reduction procedure in "hyperextended" supine position with manipulation. (a) A hand-made reduction pillow is shown. (b) The intraoperative position and "hyperextended" supine position is shown. (c) The manipulation maneuver is shown. (d) Intraoperative images are shown. The left image was taken before reduction maneuver and the right image was taken after the maneuvers. If good reduction was obtained, screw insertion was done in the same position. (e) Intraoperative fluoroscopic images pre- and postreduction maneuver. In this case, good reduction was obtained.

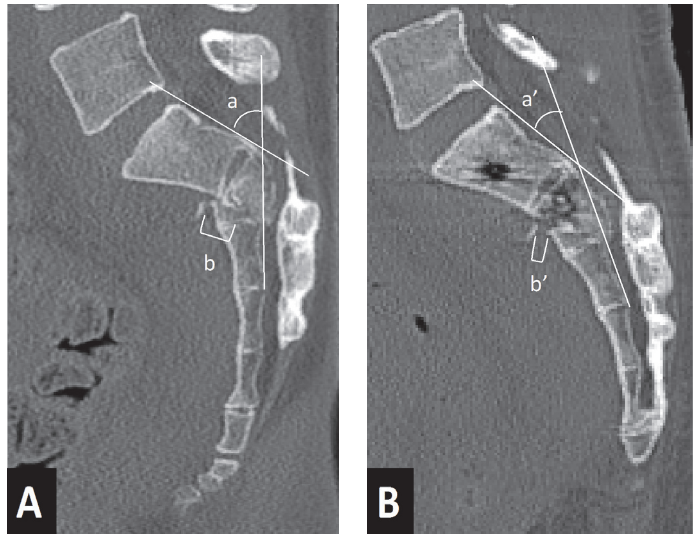
2.6. Statically Analysis. Data was enrolled through Microsoft Excel 2016 (Microsoft, Redmond, WA), followed by a statistical analysis using IBM SPSS Statistics, version 19 (SPSS, Chicago, IL). Data are given in terms of arithmetic mean and standard deviation. The initial, postoperative, and final follow-up data were analyzed using paired t-test. Data differences were considered significant for values of $p < 0.05$.

3. Results

3.1. Patient Demographics (Table 1). Sixteen patients (6 men, 10 women) with Denis zone III sacral fractures classified as AO/OTA type C pelvic injuries were identified. Table 1 presents the patient demographics, mechanism of injury, ISS, fracture patterns, initial Gibbons' grade, and operative procedures. At the time of injury, the mean age of the patients was 29.50 ± 11.12 years (range: 16–50 years). All patients sustained high-energy traumas. The mechanisms of injury included falls from a height (n = 12; 11 suicidal and 1 accidental), traffic accidents (n = 3), and crush injuries (n = 1).

The mean ISS was 25.94 ± 13.88 (range: 9–50). Thirteen of the 16 patients showed associated injuries, including 9 cases of associated injuries of the head and trunk with an Abbreviated Injury Scale Score ≥3. Other injuries of the spine and extremities were present in 10 patients, while two patients experienced pelvic fracture and urinary tract injuries. At the time of initial examination, neurological deficits were observed in 12 out of 16 patients, with a mean Gibbons' grade of 3.13 ± 1.25 (range: 1–4).

3.2. Fracture Types. The transverse fractures involved the following levels of the sacrum: S1 (n=1), S2 (n=7), S2-3 (n=2), S3 (n=3), S3-4 (n=1), S2 + S3-4 (n=1), and S2 + S3 (n=1). The fracture patterns were classified using the Roy-Camille classification system and the fracture morphology. Roy-Camille type 2 fractures occurred in 12 patients and type 3 fractures occurred in 4 patients. Further, H-shaped (n=3),



(a) (b)

Figure 2: Radiological measurement methods. (a) A preoperative CT scan of the sacrum in the sagittal plane is shown. (b) A postoperative CT scan of the sacrum in the sagittal plane is shown. a and a': sacral kyphotic angle; b and b': sacral fracture translation.

T-shaped (n=4), U-shaped (n=7), and Y-shaped fractures (n=2) were found. A Morel-Lavallée lesion was observed in 1 case, while no cases of open fracture were found.

3.3. Operative Treatment (Table 2). Posterior percutaneous internal fixation was performed between 0 and 8 days after the injury (median: 1.31 ± 2.73 days). The operative methods for posterior pelvic ring stabilization included 12 cases of 2- or 3-TSTI screw fixation only (Figures 3 and 4), 1 bilateral S1 IS and S2 TSTI screws fixation, 1 unilateral S1 and S2 IS screw fixations, and 2 bilateral S1 and S2 IS screw fixations (Figure 5). Additional primary fixation was performed in 9 patients, including pubic rami screw fixation (n=4), pubic rami plate fixation (n=1), pubic rami screw/plate and anterior sacroiliac plate fixation (n=1), symphysis plate fixation (n=2), and plate fixations for acetabular fractures (n=2) (Figure 5). The mean operative time for posterior definitive fixation was 64.69 ± 98.65 minutes (range: 10–420 minutes).

Additional operations due to remnant bone fragments and neurological deficits were performed in 5 patients, including delayed direct sacral decompression (n=5). Posterior implant removal was routinely performed in 14 patients after the fractures had healed.

3.4. Pre- and Postoperative Radiological Results (Table 2). The mean preoperative and postoperative sacral kyphotic angles were 39.44°± 20.57° (range: 13–89°) and 21.38°± 7.39° (range, 11–36°), respectively. The mean postoperative reduction angle of the sacral kyphosis was 18.06°± 15.26° (range: 2–57°). The kyphotic angle was improved with a significant difference ($p<0.05$, 95% confidence interval (CI) 9.93 to 26.19) The mean preoperative and postoperative translations were 8.69 ± 8.03 mm (range: 0–35 mm), 2.75 ± 3.97 mm (range: 0–16 mm), respectively. The mean postoperative translation reduction was 5.93 ± 4.95 mm (range: 0–19 mm). The fracture translation was also improved with a significant difference ($p<0.05$, 95%CI 3.30 to 8.57).

3.5. Radiological, Neurological, and Clinical Outcomes at Final Follow-Up (Table 2). Fifteen patients were followed for more than 12 months. At the final follow-up (mean: 27.53 ± 19.64 months; range: 12–71 months), the mean sacral kyphotic angle and reduction loss were 27.93°± 13.01° (range: 13–60°) and 5.87°± 10.40° (range: -1-32°), respectively. The kyphotic angle was decreased with a significant difference between post-OP and final follow-up ($p<0.05$, 95%CI -11.62 to -0.11). The mean sacral translation and reduction loss were 3.80 ± 6.71 mm (range: 0-24 mm) and 1.00 ± 3.00 mm (range: -2-8 mm), respectively. The translation was maintained with a no difference ($p=0.22$, 95%CI -2.66 to 0.66). The mean Gibbons' grade was 1.80 ± 1.21 (range: 1–4) and 8 out of 12 patients (66.71%) with neurological symptoms showed improvement in neurological status. The Gibbons grade was improved with a significant difference ($p<0.05$, 95%CI 0.65 to 2.02). The mean POS score was 2.93 ± 1.28 (range: 1-4). The clinical results as indicated by the POS score were good and poor in 73.3% (11/15) and 26.7% (4/15) of the patients, respectively (Table 2).

3.6. Complications. All patients showed bone union. No case of deep and/or superficial wound infection was noted. Screw loosening was observed in 3 patients; one patient had greater reduction loss (case 3; bilateral S1 and S2 IS screws, see Figure 5). Further, screw malposition was observed in 4 patients; however, in these cases, no new neurological deficits were observed postoperatively.

Table 1: Preoperative clinical data and operative procedures.

Patients No.	Age/Sex	Mechanism of Injury	Level of transverse fracture	Classifications		ISS	Day of OP	OP procedure	
				R-C	Description			Anterior	Posterior
1	25/M	FOH	S2	2	U	34	0		S1; TSTI(P), S2; TSTI(P)
2	20/M	FOH	S2	2	H	22	0	PR screw	S1; IS×2(P) S2; IS×2(P)
3	25/F	FOH	S2	2	H	29	0	acetabulum plate	S1; IS×2(P) S2; IS×2(P)
4	40/F	FOH	S2/3	2	T	43	0		S1; TSTI(P) S2; TSTI(P)
5	16/F	WTA	S3	2	Y	17	7	PR screw×2	S1; TSTI(P) S2; TSTI(P)
6	21/M	FOH	S2	2	T	13	1		S1; TSTI(F) S2; TSTI(F)
7	29/F	FOH	S2	2	U	10	0		S1; TSTI×2(F) S2; TSTI(F)
8	20/M	CR	S3/4	2	Y	35	8	PR screw, PR plate	S1; TSTI(F) S2; TSTI(F)
9	18/F	FOH	S3	2	U	50	0		S1; TSTI(F) S2; TSTI(F)
10	25/F	FOH	S3	2	H	34	0	acetabulum plate	S1; TSTI(F) S2; TSTI(F)
11	29/M	FOH	S2	3	U	9	0		S1; IS×2(P) S2; TSTI(F)
12	23/F	FOH	S2, S3/4	2	U	16	0		S1; TSTI×2(F) S2; TSTI(F)
13	50/M	FOH	S2/3	3	T	25	5	symphysis plate	S1; IS(P) S2; TSTI(F)
14	39/F	WTA	S2, S3	2	T	10	0	PR screw×2	S1; TSTI(F) S2; TSTI(F)
15	49/F	FOH	S1	3	U	50	0	symphysis plate	S1; TSTI×2(F)
16	43/F	CTA	S2	3	U	18	0	PR screw×2	S1; TSTI(F) S2; TSTI(F)

ISS: Injury Severity Score; R-C: Roy-Camille; OP: operative; TSTI: transsacral-transiliac screw; IS: iliosacral screw; U: U-shaped; H: H-shaped; T: T-shaped; FOH: fall from height; CR: crush injury; TA: traffic accident; F: female; M: male; P: partial threads screw; F: full thread screw.

Table 2: Radiological and clinical findings.

Patient No.	Kyphotic angle			Fracture translation			Gibbons		POS clinical	FU month
	Initial	post-OP	Final	Initial	Post-OP	Final	Initial	Final		
1	33	17	20	10	2	3	1	1	4	12
2	50	36	35	12	0	0	4	1	4	24
3	63	28	60	11	6	14	4	4	1	71
4	24	16	16	0	0	0	4	4	1	64
5	31	22	22	9	4	4	4	1	4	14
6	46	31	30	5	2	0	4	2	3	18
7	65	25	36	12	0	0	4	2	3	12
8	21	13	13	3	0	0	3	1	4	48
9	89	32	32	8	3	1	4	2	3	32
10	27	15	15	11	3	3	3	1	4	19
11	32	21	24	5	0	0	1	1	4	15
12	58	23	40	35	16	24	4	4	1	40
13	13	11	-	4	2	-	1	-	-	2
14	31	21	21	0	0	0	2	1	3	12
15	28	17	41	8	4	6	4	4	1	20
16	20	14	14	6	2	2	1	1	4	17

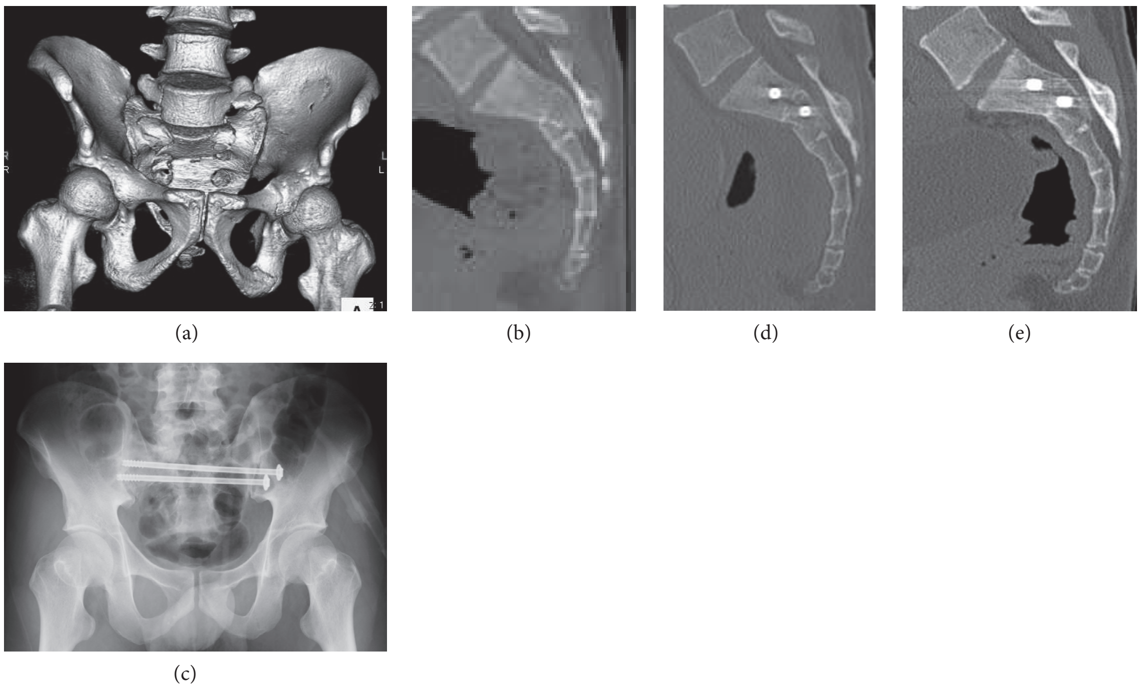


Figure 3: Case 1. A 25-year-old man who was injured from a fall from a height underwent S1 and S2 TSTI partial threaded screw fixation for a Roy-Camille type 2 U-shaped transverse sacral fracture. (a) Preoperative 3-dimensional CT reconstruction of the pelvis is shown. (b) Preoperative CT scan of the sacrum in the sagittal plane is shown (preoperative sacral kyphotic angle: 33°; fracture translation: 10 mm). (c) Postoperative anteroposterior radiograph of the pelvis is shown. (d) Postoperative CT scan of the sacrum in the sagittal plane is shown (postoperative sacral kyphotic angle: 17°; fracture translation: 2 mm). (e) Final follow-up CT scan of the sacrum in the sagittal plane is shown. Slight reduction loss was observed.

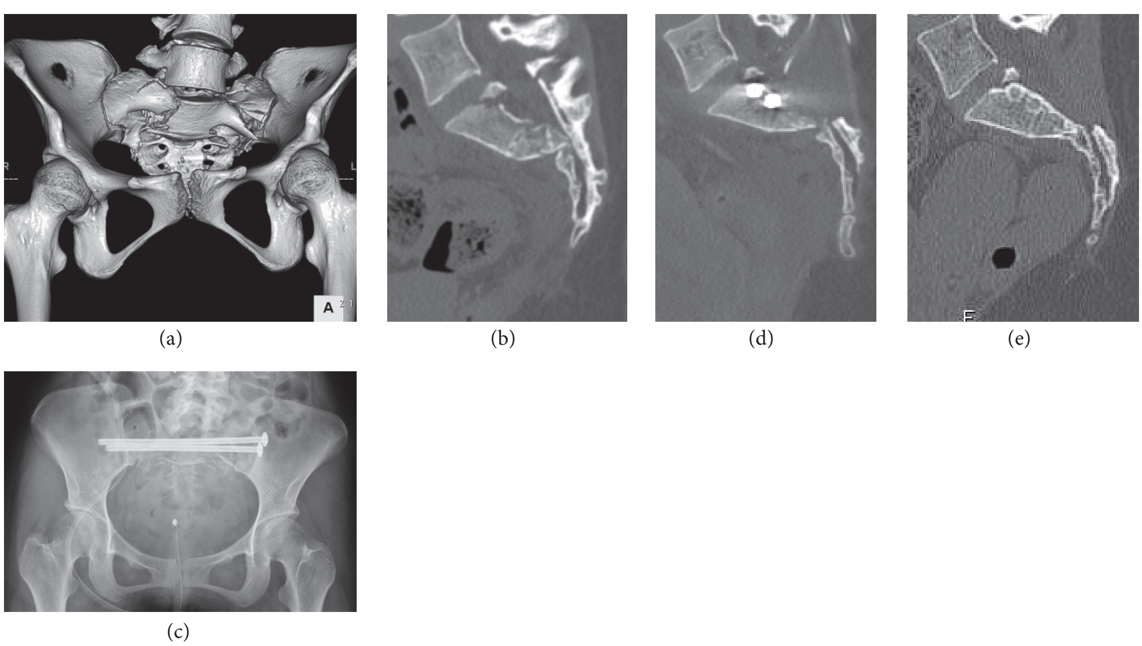
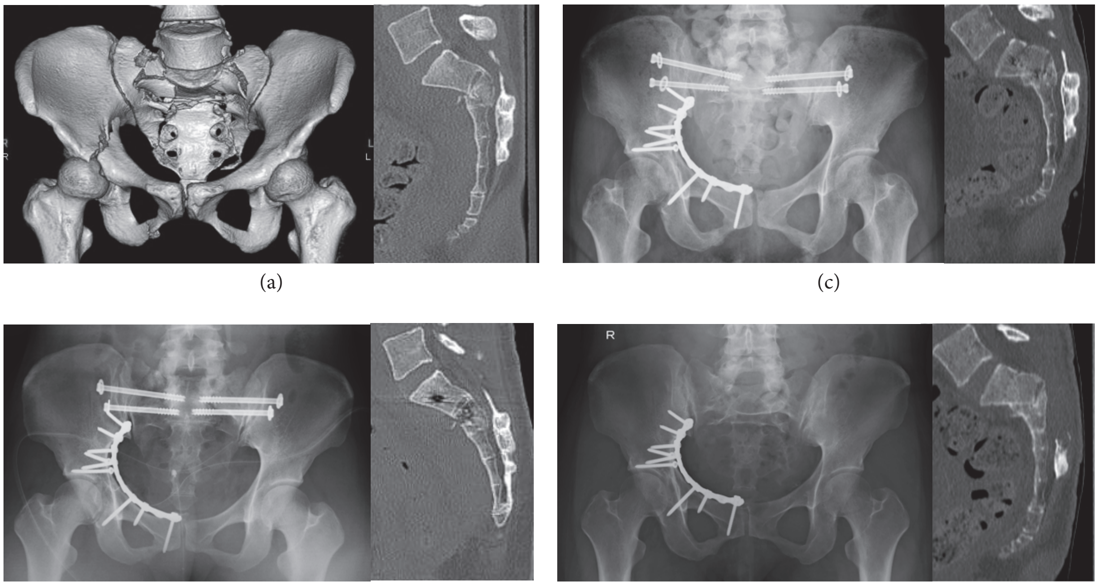


Figure 4: Case 9. An 18-year-old man who was injured from a fall from a height underwent S1 and S2 TSTI full threaded screw fixation for a Roy-Camille type 2 U-shaped transverse sacral fracture. (a) Preoperative 3-dimensional CT reconstruction of the pelvis is shown. (b) Preoperative CT scan of the sacrum in the sagittal plane is shown (preoperative sacral kyphotic angle: 89°; fracture translation: 8 mm). (c) Postoperative anteroposterior radiograph of the pelvis is shown. (d) Postoperative CT scan of the sacrum in the sagittal plane is shown (preoperative sacral kyphotic angle: 32°; fracture translation: 3 mm). (e) Final follow-up CT scan of the sacrum in the sagittal plane is shown. Good reduction quality was maintained.



(a) (c)

(b) (d)

Figure 5: Case 3. This case had the greatest loss of reduction. A 25-year-old woman who was injured from a fall from a height underwent unilateral S1 and S2 bilateral iliosacral partial threaded screw fixation for a Roy-Camille type 2 H-shaped transverse sacral fracture. (a) Preoperative 3-dimensional and sagittal plane CT reconstruction of the pelvis is shown (preoperative sacral kyphotic angle: 63°; fracture translation: 11 mm). (b) Postoperative anteroposterior radiograph and CT scan of the sacrum in the sagittal plane is shown (postoperative sacral kyphotic angle: 28°; fracture translation: 6 mm). (c) The anteroposterior radiograph and CT scan of the sacrum in the sagittal plane taken one month after the initial operative treatment is shown (sacral kyphotic angle: 60°; fracture translation: 14 mm). IS screw loosening was observed. Secondary sacral decompression was performed. (d) Final follow-up anteroposterior radiograph and CT scan of the sacrum in the sagittal plane is shown. Bone healing was achieved, but reduction loss and bladder/bowel dysfunction remained.

4. Discussion

The present study aimed to show that closed reduction in a hyperextended supine position with manipulations and percutaneous TSTI/IS screw fixation is useful for treating Denis zone III sacral fractures. Currently, the present study is the largest case series regarding closed reduction and percutaneous screw fixation for these fractures [8, 10, 11, 13]. Furthermore, the present study includes the greatest number of cases involving the supine position maneuver.

Denis zone III sacral fractures may be H-, U-, T-, or Y-shaped [20], and sacral dislocations may be anterior or posterior [1]. When treating these fractures, it is important to reduce the sacral kyphotic angle fracture translation and to maintain this reduced position. Previously, the outcomes of several treatments for these fractures have been reported. Siebler et al. reported the results of conservative treatment [21], and found that the sacral kyphotic angle increased by 4.1° (from 36.4° to 40.5°) posttreatment. In terms of operative treatment, Schildhauer et al., Tan et al., and Lindahl et al. reported that using spinopelvic fixation, the initial kyphotic angles of 43°, 32°, and 38° were improved to the final angles of 21°, 19°, and 22°, respectively [6, 20, 22]. Nork et al. reported that, after using IS screw fixation, the kyphotic angle was reduced from 29.2° to 28.2° [8], whereas König et al. reported that, after using TSTI screw fixation in 3 patients, the sacrococcygeal and pelvic incidence angles were reduced from 84° and 75° preoperatively to 58° and 56° postoperatively, respectively (reduction losses of 14° and 15°, respectively) [10]. Ruatti et al. reported that, in a supine position, hyperlordosis, skeletal traction, and percutaneous IS screw fixation had good reduction results in 3 cases [13]. In the present study, the pre- and postoperative kyphotic angles were 40° and 22°, respectively, indicating a reduction loss of 4.9°. In terms of translation, Lindahl et al. reported that the mean pre- and postoperative translations with spinopelvic fixation were 15.5 and 5.8 mm, respectively [22], whereas in the present study, the corresponding values were 8.9 and 2.8 mm. In the present study, one patient with IS fixation only (Case 3) was observed to have a high reduction loss and screw loosening. Taken together, these clinical data suggest that TSTI screw fixation is equal to spinopelvic fixation. Furthermore, Min et al. reported that 2-TSTI screw fixation was superior to spinopelvic fixation in a zone 2 sacral fracture model from a biomechanical viewpoint [23]. Therefore, we believe that TSTI screw fixation in the supine position is an effective, rigid, and minimally invasive procedure for Denis zone III sacral fracture fixation.

Denis zone III sacral fractures have been reported to result in neurological injury of varying severity in up to 100% of patients [6–8, 20–22, 24]. Accordingly, in the present study, neurological deficits were seen in 12 of 16 patients (75%). However, neurological recovery has been shown to occur in 50–100% of patients with these fractures [6–8, 10, 20, 21]. Early surgical treatment of the sacrum, including restoration of spinopelvic stability and decompression of the nerve roots, indirectly or directly, is thought to provide the best possible environment for neurological recovery. Schildhauer et al. reported that neurological recovery depends on the extent of nerve damage at the time of injury [6]. However, Siebler et al., in their study of nonoperative treatment, reported that the recovery rate was still as high as 85.7%. [21] Thus, the best treatment method, in terms of neurological outcomes, remains unclear. In the present study, the overall neurological recovery rate was 66.7% (8/12). A lack of neurological recovery was observed in four cases (cases 3, 4, 12, and 15). Of these, one case (case 4) involved a spinal cord injury merger. In an additional case (cases 12), decompression of the postoperative sacral canal was deemed sufficient; however, no neurological recovery was observed. In cases 3 and 15, because of a suspected reduction loss in the kyphotic angle and translation, additional nerve decompression surgery was performed (case 3); however, nerve recovery could not be obtained. In addition, four cases (cases 6, 7, 8, and 9; see Figure 4) underwent additional decompression because of remnant fragment and/or insufficient neurological recovery and were finally considered to have sufficient neurological recovery. Based on our experience and the report by Schildhauer et al. [6], the likelihood of neurological recovery appears to be dependent on the degree of nerve damage at the time of injury. However, for maximum neurological recovery, we consider indirect or direct nerve decompression to be necessary. Hence, in our treatment strategy, indirect reduction and decompression are performed in the acute phase and if the postoperative CT shows incomplete decompression and/or remnant fracture fragments in the sacral canal, secondary direct sacral decompression is consequently performed.

We consider TSTI/IS screw fixation to be a less invasive method, associated with a relatively low complication rate. In our series, the mean operative time was approximately 65 minutes. In cases involving TSTI or IS screw insertion only, the screw insertion time was approximately 10 minutes per screw. In addition, the time required for our preoperative closed reduction procedure is about 20 to 30 minutes. Hence, in cases requiring only closed reduction and screw fixation, patients can be treated in the acute phase. Furthermore, in cases involving screw fixation only, the patient is positioned supine, which is often the most comfortable position for polytrauma patients. In addition, TSTI/IS screw fixation is associated with a very low profile and few surgical site complications. In fact, in our study, no surgical site complications were observed. In past reports using different approaches, the surgical site complication rate was as high as 38% [6, 7, 20]. Spinopelvic fixation is associated with a particularly high complication rate in pelvic ring fracture treatment [6, 20], and posterior soft tissue complications are associated with poorer outcomes.

There are several limitations to the present study. First, the study population was relatively small and did not allow for a highly powered statistical analysis; therefore, our conclusions should be interpreted with caution. Second, there are operative limitations for TSTI/IS screw fixation. In TSTI/IS screw fixation for zone III sacral fractures, at least two screw insertions (2 TSTI screws, or 1 TSTI screw and 1 IS screw) are required, as the screws need to provide resistance against the vertical load shear force and the rotational force of the sacral vertebral body. However, it has been reported that ilio-sacro-iliacal corridors for intraosseous implants were not inserted in 18–25% and 10–12% of S1 and S2 cases, respectively; moreover, a high frequency of this issue has been reported for female patients [25–27]. Thus, owing to anatomical variance and different fracture types, this method is not always useful.

In conclusion, the current study showed that closed reduction in a hyperextended supine position with TSTI/IS screw fixation is effective for treating Denis zone III sacral fractures in terms of the fracture reduction, loss of reduction, neurological recovery, and clinical outcomes. Thus, despite some limitations, we believe that our procedure is an effective and appropriate method for treating Denis zone III sacral fractures.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

None of the authors has received any financial or personal support from other people or organizations that could inappropriately influence this work.

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Research Article

Spinopelvic Dissociation: Comparison of Outcomes of Percutaneous versus Open Fixation Strategies

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Introduction. Spinopelvic dissociation injuries are historically treated with open reduction with or without decompressive laminectomy. Recent technological advances have allowed for percutaneous fixation with indirect reduction. Herein, we evaluate outcomes and complications between patients treated with open reduction versus percutaneous spinopelvic fixation. *Methods.* Retrospective review of patients undergoing spinopelvic fixation from a single, level one trauma center from 2012 to 2017. Patient information regarding demographics, associated injuries, and treatment outcome measures was recorded and analyzed. All fractures were classified via the AO Spine classification system. *Results.* Thirty-one spinopelvic dissociations were identified: 15 treated with open and 16 with percutaneous techniques. The two treatment groups had similar preoperative characteristics including spinopelvic parameters (pelvic incidence and lumbar lordosis). Compared to open reduction internal fixation, percutaneous fixation of spinopelvic dissociation resulted in statistically significantly lower blood loss (171 cc versus 538 cc; $p = 0.0013$). There were no significant differences in surgical site infections ($p = 0.48$) or operating room time ($p = 0.66$). *Conclusion.* Percutaneous fixation of spinopelvic dissociation is associated with significantly less blood loss. Treatment outcomes in terms of infection, length of stay, operative cost, and final alignment between the open and percutaneous group were similar.

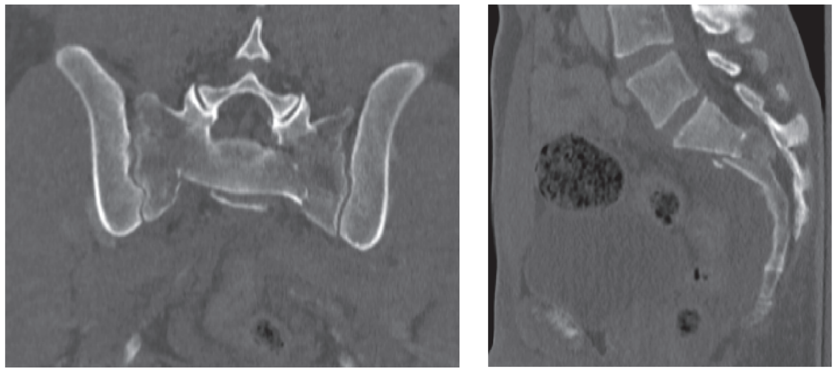
1. Introduction

Spinopelvic dissociation or U type sacrum fracture is a rare injury that involves a transverse sacral fracture pattern and can be associated with a high rate of neurologic injury, up to 57% (Figure 1) [1–4]. In large case series, spinopelvic dissociative injuries account for only 2.9% of all pelvic ring traumas [5, 6]. Traditional treatment methods involving open reduction with internal fixation have been observed to have high rates of postoperative infections up to 14–16% [7–10]. In the last decade, percutaneous fixation (Figure 2) of these injuries has gained popularity with reported improved clinical outcomes [11, 12].

Herein, we critically evaluate results of spinopelvic dissociations treated with either percutaneous or open reduction. To our knowledge, this is the largest series of patients with spinopelvic dissociation treated surgically. We hypothesized that percutaneous fixation of spinopelvic dissociation using minimally invasive fusion from lumbar four or five to pelvis would result in shorter operative time, fewer postoperative transfusions, and decreased estimated blood loss while adequately reestablishing spinopelvic parameters.

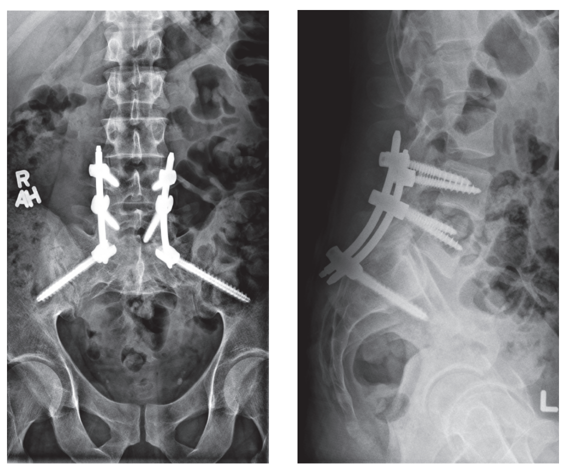
2. Methods

A retrospective review was conducted on all operatively managed spinopelvic dissociations treated between January 2012 and March 2017 at a single, level one trauma center. Institutional review board approval was obtained. Inclusion criteria were patients over 18 years of age with diagnosed spinopelvic dissociation based on pelvic X-rays and CT scans. Patients with preoperative lower lumbar, sacral, or pelvic hardware were excluded. Patient characteristics and demographics



(a) (b)

Figure 1: Coronal (a) and midsagittal (b) preoperative CT scan. Note the bilateral sacral fractures with horizontal S2 fracture with a 37-degree kyphotic deformity.



(a) (b)

Figure 2: AP (a) and lateral (b) radiographs of patient seen in Figure 1 at 16 months postoperatively treated with percutaneous fixation. Note the resolution of kyphotic deformity with consolidation of fracture lines.

were collected for all patients including age, gender, mechanism of injury, associated injuries, neurological injury, and tobacco use. The injuries were classified according to the Arbeitsgemeinschaft für Osteosynthesefragen (AO) sacrum classification. Pelvic X-rays were also subclassified based on modifiers M3 being anterior pelvic ring injury and M4 sacroiliac joint injury [13].

All surgeries were performed by fellowship-trained spine, orthopedic surgeons during this initial inpatient stay. The decision of open versus percutaneous fixation was nonrandomized and at the judgment of the attending surgeon. This was usually based on associated injuries such as soft tissue near a possible incision site, body habitus, and surgeon training. Younger trained surgeons tended to perform percutaneous procedures while older ones tended to perform traditional open reduction techniques. All percutaneous surgeries used indirect reduction and four or five percutaneous lumbar pedicle screws with iliac fixation as described by Wang et al. [11]. Percutaneous transsacral fixation was not used in any of the patients. Neurological dysfunction (cauda equina or sacral nerve root disruption) was treated with either laminectomies or fracture reduction with indirect decompression.

The surgical procedure began with standard spinal monitoring and general anesthesia. The patients were positioned prone on an open top table with large bumps under the thighs to accentuate an extension force on the legs. This high extension was our main reduction maneuver in the surgical procedure. Bilateral L5 pedicle screws were placed under fluoroscopic guidance with Jamshidi needles, and these were also used for the iliac fixation. Initial placement of the needle for iliac fixation was just ventromedial to the PSIS. From this point using a teardrop view, the Jamshidi needle was guided down between the inner and the outer tables of the pelvis. Following placement of the needle, inlet, outlet, and lateral views were obtained to ensure no violation of the sciatic notch.

In-hospital clinical outcomes were measured and included surgical site infection, transfusions within 72 hours postoperatively, operative time, and estimated blood loss.

Table 1: Preoperative patient characteristics.

	Open (n = 15)	Closed (n = 16)	p value
Age	44.86	37.87	0.3046
Gender	Male: 9 Female: 6	Male: 11 Female: 5	0.7160
Tobacco use	8 (53%)	8 (50%)	0.4589
Cauda equina	3 (20%)	3 (18%)	1.00

After discharge, patients were followed up at routine intervals as outpatients. Postoperative complications including hardware irritation and spinopelvic parameters (pelvic incidence and lumbar lordosis) were recorded for all patients. All patients were made weight bearing as tolerated unless other lower extremity fractures prohibited this.

Demographic, clinical, and outcome measures were compared between the fixation groups using Fisher's exact test and Student's t-test for categorical and continuous variables, respectively. p values ≤ 0.05 (two-sided) were considered statistically significant.

3. Results

Thirty-one patients with spinopelvic dissociation were identified at our institution from 2012 to 2017. The cohort consisted of 15 patients treated with open reduction and lumbopelvic fixation and 16 with indirect reduction and percutaneous lumbopelvic fixation. Age, sex, and tobacco use were similar between the two groups ($p > 0.05$) (Table 1). Outpatient follow-up was on average 7.8 months for the open group and 9.9 months for the closed group ($p = 0.50$). Both groups included three patients with preoperative symptoms of cauda equina.

Injury patterns were classified based on the AO sacrum classification system [13]. Our results can be found in Table 2. Fractures were classified as nondisplaced sacral U type variant (C0), sacral U type variant without posterior instability (C1), bilateral complete type B fractures without transverse fracture (C2), and displaced U type sacrum fracture (C3). In addition to these categories, fractures were also classified based on modifiers of anterior pelvic ring injury (M3) and sacroiliac joint injury (M4). Of the 15 open procedures, 5 were C0, 1 was C2, and 9 were C3. Of these 15, a total of 6 were M3 modifiers signifying anterior pelvic ring injury. Of the 16 percutaneous procedures, 8 were classified as C0 and 8 were C3. Five from the C0 percutaneous subgroup had M3 modifiers. Of the C3 group, 2 had an anterior ring injury (M3), 1 had a posterior sacroiliac joint disruption (M4), and a total of 2 had both modifiers (M3, M4). This information can be found in Table 2.

Associated injuries are shown in Table 3. The cohort of 31 patients included 18 (58%) with long bone fractures (8 in the open and 10 in the closed group) that prompted surgical treatment. Other associated injuries included closed head injuries (42%), acetabular fractures (39%), and other spine fractures (48%).

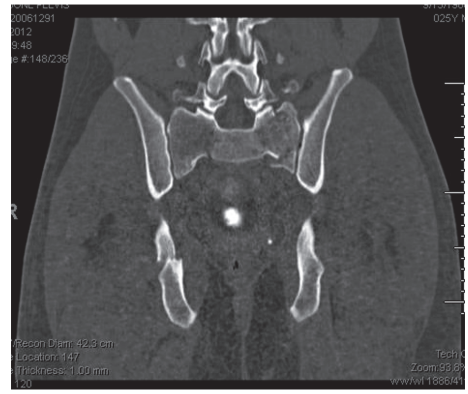


Figure 3: Preoperative coronal CT scan of a patient with spinopelvic dissociation.

Postoperative outcomes are shown in Table 4. Mean intraoperative blood loss was significantly higher ($p = 0.0013$) in the open reduction (538 cc) group in comparison to the percutaneous group (171 cc). Transfusions within 72 hours postoperatively were seen in seven patients (43%) treated with percutaneous fixation and in three patients (20%) treated with open reduction ($p = 0.25$). Average length of stay for the open group was 14.9 days and 17.5 days in the percutaneous group ($p = 0.57$). OR cost for the percutaneous procedure averaged at $83,705.80 per case and $63,963.13 for the open procedure ($p = 0.29$).

Postoperatively, spinopelvic radiographic parameters (lumbar lordosis and pelvic incidence) were similar between the two groups (Table 3). Average lumbar lordosis was 54.1 degrees in the open group and 53.8 degrees in the percutaneous group ($p = 0.96$). Pelvic incidence was 65.8 degrees in the open group and 64.7 degrees in the closed group ($p = 0.84$). No surgical site infections were seen in the percutaneous treatment cohort, whereas one infection was observed with the open reduction cohort ($p = 0.48$). A comparable amount in each group underwent hardware removal at a later date; 40% (6/15) in the open group and 31% (5/16) in the closed group underwent hardware removal ($p = 0.72$). Figures 3 and 4 show another example of patients in our cohort. This shows pre- and postoperative images for fixation with open reduction internal fixation.

4. Discussion

Modern technologic advances in orthopedic instrumentation have allowed for the adoption of percutaneous techniques to treat spinopelvic dissociation. Historic treatment with open reduction with lumbopelvic fixation of spinopelvic dissociation has been associated with a high infection rate [9, 10]. Schildhauer et al. observed an infection rate of 16% with open reduction and internal fixation of spinopelvic dissociations [8]. With current minimally invasive strategies, percutaneous instrumentation has been shown to have low rates of wound complication and decreased blood loss [12].

In the current study, we compared surgical as well as postoperative outcomes of open versus percutaneous fixation

Table 2: Fracture pattern classification. All fracture patterns were AO sacrum classification type C.

AO Spine	C0 (nondisplaced U type sacrum fracture)				C1 (alternative sacrum U type fracture without posterior instability)				C2 (bilateral complete type B injuries without transverse fracture)				C3 (displaced U type sacrum fracture)			
Modifiers	–	M3	M4	M3, 4	–	M3	M4	M3, 4	–	M3	M4	M3, 4	–	M3	M4	M3, 4
Open	5	2			0				1	1			9	3		
Closed	8	5			0				0				8	2	1	2

Table 3: Associated traumatic injuries.

	Open ($n = 15$)	Closed ($n = 16$)	Total ($n = 31$)
Traumatic brain injury	2 (13%)	1 (6%)	3 (10%)
Closed head injury	9 (60%)	4 (25%)	13 (42%)
Extremity fracture	8 (53%)	10 (63%)	18 (58%)
Anterior pelvic ring fracture	6 (40%)	11 (69%)	17 (55%)
Acetabulum fracture	4 (27%)	5 (31%)	9 (29%)
Thoracic injury	7 (47%)	10 (63%)	17 (55%)
Blunt abdominal injury	4 (27%)	6 (38%)	10 (32%)
Associated spine injury	6 (40%)	9 (56%)	15 (48%)

Figure 4: Postoperative films of patient treated with open reduction internal fixation of spinopelvic dissociation.

in a cohort of 31 patients. To our knowledge, this is the largest study to be reported on patients with spinopelvic dissociation treated surgically [9, 12, 14]. Through utilizing indirect reduction techniques as described by Nork et al., we were able to show satisfactory fracture reduction with equivalent (p = 0.96, 0.84) postoperative lumbar lordosis (LL) and pelvic incidence (PI) in both treatment groups [5, 15]. The limitation of our study is that spinopelvic measures were primarily evaluated compared to the actual reduction of the fracture site. Though there is individual variability in the spinopelvic parameters, studies have shown that it can be used as a surrogate of fracture reduction in the sagittal plane and the primary driver of clinical outcome [16].

In the current study, percutaneous fixation of spinopelvic dissociation showed a statistically lower intraoperative blood loss compared to open reduction internal fixation (171 cc versus 528 cc, $p = 0.0013$) and a lower rate of postoperative infections (1 versus 0, $p = 0.483$). Blood loss is difficult to analyze as a sole outcome when associated injuries are not taken into account. Aside from traumatic brain injury and closed head injury, the closed cohort had more associated injuries than the open group (Table 4). This discrepancy in preoperative patient characteristics likely explains the increased length of stay in our percutaneous group compared to the cohort. Despite the procedure being one that results in less blood loss and shorter operative time, the percutaneous patient population had more injuries on average than the open group, likely resulting in a longer hospital stay. Our results correlate with the literature seen with minimally invasive spine (MIS) that emphasized improved short-term clinical outcomes with percutaneous technology [17–20]. Meta-analysis by Phan and colleagues confirmed no excessive screw malposition, decreased infection, and decreased hospital stay with percutaneous spinal techniques [20]. Furthermore, given the severe nature of the trauma sustained by patients with spinopelvic dissociation, these patients are undergoing many procedures for various injuries such as long bone fractures. In settings such as this, the benefits of minimally invasive procedures cannot be overstated.

One surgical site infection was observed in the cohort. The patient was involved in an ATV accident and sustained a type C3, M3 (AO Spine classification) spinopelvic dissociation in addition to anterior pelvic ring disruption with 5 cm of pubic symphysis diastasis. Ten days after a combined anterior pelvic ring and open posterior spinopelvic fixation, the patient underwent debridement with retention of hardware. With prolonged IV antibiotics, the patient progressed to bony union without any further intervention.

Operative time was twenty-nine minutes shorter in the percutaneous group in comparison to the open group. While

Table 4: Postoperative outcomes on operatively treated patients. Note that blood loss was statistically significantly less in the percutaneous cohort.

	Open (n = 15)	Closed (n = 16)	p value
Pelvic incidence	65.8°	64.68°	0.8413
Lumbar lordosis	54.14°	53.81°	0.9568
Surgical site infection	1 (6.67%)	0 (0%)	0.4839
Transfusion post-op	3 (20%)	7 (43%)	0.2524
Operative time (minutes)	311	282	0.6665
Estimated blood loss (cc)	538	17	0.0013
Hardware removal	6 (40%)	5 (31%)	0.7160
Length of hospital stay (days)	14.91	17.45	0.5696
Length of follow-up (months)	7.75	9.93	0.5042
OR charges	$249,387.95	$347,205.22	0.1837
OR cost	63,963.13	$83,705.80	0.2922

this relationship does not meet statistical significance, it is of clinical and financial importance. Work by Macario estimates that operating room time per minute in US hospitals costs an average of $62 [21]. In review of our hospitals' cost data, we found that the total cost for the percutaneous group was greater ($p = 0.29$) than of the open treatment group. This increased cost is likely due to many factors such as using new percutaneous implants and intraoperative navigation; however, as itemized cost data were not available, we are unable to pinpoint an exact reason for the difference in cost. Further, we noted that there were decreased operative times in the percutaneous group despite the rising learning curve of the surgeon and the fluoroscopy staff.

Sacral laminectomy and decompression were performed only in patients who had focal compression of sacral nerve roots. In our study, 6 of the 31 displaying bowel and bladder dysfunction did not have decompression. Unlike cauda equina of the lumbar spine, neurological injuries secondary to sacral fractures are not considered neurologic emergencies requiring decompression within 48 hours. Schildhauer and colleagues showed that surgical timing did not correlate with clinical outcomes in patients with cauda equina secondary to spinopelvic dissociation [8]. This was confirmed by Lindahl et al. who additionally showed that laminectomy did not improve bladder or bowel function in patients who underwent decompression [22]. The role of open sacral decompression on ultimate outcome remains unclear and is beyond the scope of the current study. As shown earlier, the reduction of the fracture via percutaneous methods is comparable to that obtained with open reduction internal fixation. Figure 3 shows the pre- and postoperative imaging for a patient who underwent percutaneous fixation whereas Figure 4 shows the same imaging with an open reduction. As evidenced here, similar reduction can be obtained without the need for an invasive approach.

There are several limitations to this study including those inherent to a retrospective review. First and foremost, selection bias plays a role in all retrospective reviews. The decision to treat injuries, open versus closed, was based on the surgeon's preference and experience. Factors going into choosing which intervention a patient underwent are likely related to physician preference as well as body habitus, overall physiologic health, and underlying comorbidities. The majority of our patient selection was based on the age and training of the surgeon. The two younger physicians with more recent training tended to perform percutaneous techniques whereas the older physicians performed open reduction. The type of surgical skill necessary for both open and closed procedures varies as well. In the percutaneous procedure, one must master positioning of the Jamshidi needle in space while correlating this to the radiographic images. This type of procedure does not involve sacral laminectomy and the fine dexterity required in this aspect of an open approach. The patients reviewed were subject to care under several different surgeons and were nonrandomized to treatment groups. Unfortunately, the retrospective chart review did not include information on the soft tissue condition of the patients. This would have certainly affected the decision-making of the treating team had this been documented in the chart. Given the severe nature of the trauma sustained by these patients, it is inherently difficult to independently evaluate outcomes of a single procedure given their multisystem traumatic injuries. As Table 3 shows, the shear nature of the diversity of these patients and their extensive injuries makes a thorough comparison of these two patient groups difficult. Though it is a large series on an infrequently encountered injury, larger and better powered studies are required to further validate our results. We recognize the relatively short follow-up for this cohort and the need for longer studies to fully evaluate the effects of open versus closed surgical treatment in these patients.

In conclusion, percutaneous fixation of spinopelvic dissociation showed superior outcomes compared to open reduction internal fixation. Percutaneous fixation allowed for a statistically significant decrease in operative blood loss, while also showing a trend of decreasing the operating room time and surgical site infection. Though biomechanically triangular osteosynthesis is superior to stand-alone lumbopelvic fixation, clinically stand-alone fixation without the addition of iliosacral screws results in good outcomes in our series. Percutaneous fixation of spinopelvic dissociation is a less morbid and more expeditious method of pelvic stabilization compared to open reduction internal fixation.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication or content of this manuscript.

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Clinical Study

Percutaneous Injection of Strontium Containing Hydroxyapatite versus Polymethacrylate Plus Short-Segment Pedicle Screw Fixation for Traumatic A2- and A3/AO-Type Fractures in Adults

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Introduction. Polymethacrylate (PMMA) is commonly used in vertebroplasty and balloon kyphoplasty, but its use has been associated with complications. This study tests three hypotheses: (1) whether strontium hydroxyapatite (Sr-HA) is equivalent to PMMA for restoring thoracolumbar vertebral body fractures, (2) whether the incidence of PMMA leakage is similar to that of Sr-HA leakage, and (3) whether Sr-HAis is resorbed and substituted by new vertebral bone. *Materials and Methods*. Two age- and sex-matched groups received short percutaneous pedicle screw fixation plus PEEK implant (Kiva, VCF Treatment System, Benvenue Medical, Santa Clara, CA, USA) filled with either Sr-HA (Group A) or PMMA (Group B) after A2- and A3/AO-type thoracolumbar vertebral body fractures. The Visual Analog Scale (VAS) score and imaging parameters, which included segmental kyphosis angle (SKA), vertebral body height ratios (VBHr), spinal canal encroachment (SCE), bone cement leakage, and Sr-HA resorption, were compared between the two groups. *Results*. The average follow-up was 28 months. No differences in VAS scores between Groups A and B were observed at baseline. Baseline back pain in both groups improved significantly three months postoperatively. Anterior, middle, and posterior VBHr did not differ between the two groups at any time point. SKA was improved insignificantly in both groups. SCE decreased insignificantly in both groups on 12-month follow-up using computed tomography (CT). PMMA leakage was observed in one patient, while no Sr-HA paste leakages occurred. Sr-HA resorption and replacement with vertebral bone were observed, and no new fractures were observed. *Conclusions*. As all hypotheses were confirmed, the authors recommend the use of Sr-HA instead of PMMA in traumatic spine fractures, although more patients and longer follow-up will be needed to strengthen these results. This trial is registered with NCT03431519.

1. Introduction

Polymethacrylate (PMMA) is commonly used in vertebroplasty (VP) and balloon kyphoplasty (BK) for osteoporotic and fresh thoracolumbar fractures. VP and BK can be used either alone or in combination with pedicle screw constructs. However, PMMA has been reported to be associated with undesirable properties such as high setting temperature, leakage (7–10%), lung and distal emboli, lack of osseointegration, and significant stiffness mismatch with bone leading to subsequent adjacent fractures or even refracture of the augmented vertebra [1]. In consideration of these potential complications, biological and bioactive bone substitutes (calcium phosphate, Sr-HA, etc.) have been used in an attempt to reduce the undesirable events associated with PMMA, while enhancing the mechanical stability of osteoporotic vertebral compression fractures. Compared with PMMA, significantly lower leakage rates have been reported with biologic and bioactive bone cements [1–7].

Strontium (Sr) is an antiosteoporosis agent, which has dual effects on bone metabolism [8]. Sr restores the bone turnover balance, especially when the treatment of bone fractures caused by osteoporosis is challenging [9, 10]. *In vitro* studies have shown that Sr acts through the calcium-sensing receptor to increase the mRNA level of osteoprotegerin and decrease the mRNA levels of the receptor activator of nuclear factor-kappaB ligand [11]. Furthermore, Sr promotes bone formation by stimulating the differentiation of osteoblasts, as well as by blocking bone resorption through inhibition of osteoclast differentiation [11]. A 10-year clinical trial reported that Sr reduces the risk of vertebral and nonvertebral fractures and increases bone mineral density [11].

Sr-HA exhibits radiopacity three times greater than that of cortical bone and thus has enhanced visibility compared to bone. This is an advantage from the perspective of clinical imaging when it is used to assess implant placement and osseointegration at the bone-implant interface [12, 13].

Previous investigations have not identified any adverse reactions associated with Sr-HA use (such as foreign body reaction, inflammation, or bone necrosis). This is likely because of the nontoxicity of bisphenol-A bis(2-hydroxypropyl)methacrylate (BISGMA) and the lower setting temperature of Sr-HA [6, 12, 14].

Clinical studies reporting the use of Sr-HA in VP and BK for vertebral compression fractures are lacking [5]. An experimental study showed that Sr-HA facilitated reconstruction and maintenance of vertebral body height. It was also reported that Sr-HA is incorporated in the fractured vertebral body during bone remodeling by 3 to 6 months after the VP [5]. In an animal study, new lamellar bone grew onto the Sr-HA, soon after surgery [15].

Since biologic and bioactive cements do not provide immediate stability like PMMA can, several authors are currently performing BK and VP procedures for A2- and A3/AO-type thoracolumbar fractures using titanium stents and PEEK devices, supplemented with short-segment pedicle screws, to increase immediate stability [16–18].

Taking into consideration the biological properties of Sr-HA bioactive bone cement, the authors of this study have been using Sr-HA with PEEK implants together with percutaneous pedicle screw fixation in selected young adult patients with fresh, severely compressed, A2- and A3/AO-type thoracolumbar fractures. The aim of this preliminary comparative study was to examine the short- to medium-term efficacy of percutaneous vertebral body reconstruction by vertebral body augmentation with Sr-HA paste plus short-segment pedicle screw fixation in fresh fractures, as well as evaluate Sr-HA resorption/substitution. The hypotheses tested in this prospective comparative controlled study were as follows: (1) whether Sr-HA is equivalent to PMMA for restoring the fractured thoracolumbar vertebral body, (2) whether leakage of Sr-HA is less than that of PMMA, and (3) whether Sr-HA is completely resorbed and replaced by cancellous bone.

2. Methods

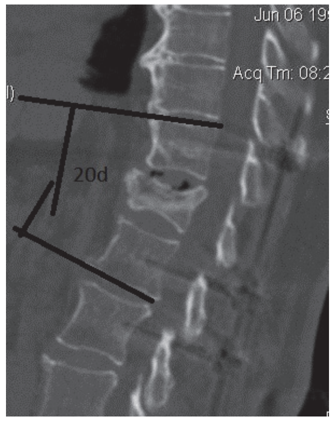
2.1. Patients. This study was approved by the institutional ethical committee and all patients gave written informed consent. From April to December 2013, thirty-eight (38) consecutive adult female patients were selected and divided into two groups, each consisting of 19 age-matched individuals. Each of the subjects had a single, severely (>40%) compressed A2- and A3/AO-type thoracolumbar (T10-L3) fracture, without any serious concomitant injuries. For treatment of the fractures, the subjects received VP with PEEK and either Sr-HA (Group A) or PMMA (Group B). A total of 8 patients (4 in each group) were excluded from the final evaluation for the following reasons: one patient was excluded because her intraoperative biopsy revealed metastatic disease; six patients were excluded because they were not available for further evaluation after the 3-month follow-up; and one patient was excluded because of a deep-tissue infection. Finally, each of the two groups included 15 age-matched ($P = 0.52$) adult female patients. Group A included 15 women aged 45.7 ± 8 years (range: 38–53 years), and Group B included 15 women aged 46 ± 6 years (range: 40–52 years) at the time of the index surgery. The body mass index (BMI) of the subjects in Group A averaged 28 ± 5 (range: 19–39) and in Group B averaged 26 ± 3 (range: 22–30) ($P = 0.32$). All patients from both groups were attended by the same senior spine surgeon and underwent percutaneous short pedicle screw fixation plus vertebroplasty with PEEK implants (Kiva, VCF Treatment System, Benvenue Medical, Santa Clara, CA, USA) filled with either Sr-HA paste (Neogel, Teknimed, Vic-en-Bigorre, France) (Group A) or low-viscosity PMMA (Group B).

Patients were excluded from the study in cases of polytrauma, neurologic impairment, spinal deformity, known malignancy, and previous fracture or surgery in the same or adjacent vertebrae. Back pain intensity was recorded using the VAS scoring system (10-point scale).

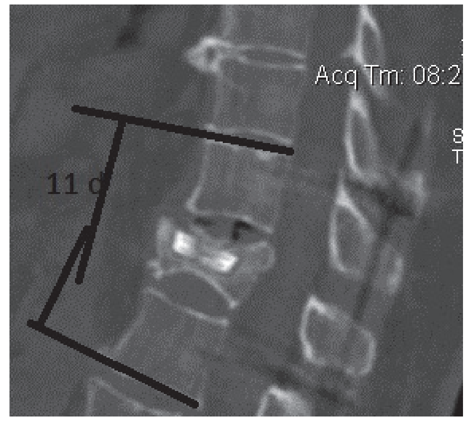
Patients were randomly assigned to receive either Sr-HA or PMMA, and the process was blinded by the following method: the second author randomized the patients to receive either PMMA or Sr-HA without knowledge of the patients' names. The surgeons were unaware of which patients would receive Sr-HA or PMMA.

The operation was performed in the prone position. Two multiaxial, cannulated pedicle screws with diameters of 6-7 mm were inserted into the vertebrae immediately superior and inferior to the fractured vertebra via stab incisions using an image intensifier. One PEEK implant was introduced unilaterally through the pedicle to reduce the likelihood of vertebral body collapse, and subsequently the filling material, PMMA or Sr-HA, was injected. A column of either PMMA or Sr-HA was constructed inside the PEEK implant. Next, two longitudinal, appropriately contoured rods were percutaneously inserted and assembled with the pedicle screws in each side. Supine, anteroposterior, and lateral digital roentgenograms of the thoracolumbar spine were taken on admission. Standing digital roentgenograms of the whole spine were taken on the second postoperative day, 6 months postoperatively, and at the final observation (average follow-up of 28 months). CT scans were performed preoperatively and at 12 months postoperatively to evaluate the spinal canal remodeling, the Sr-HA resorption, and the bone healing state in the fractured vertebral body.

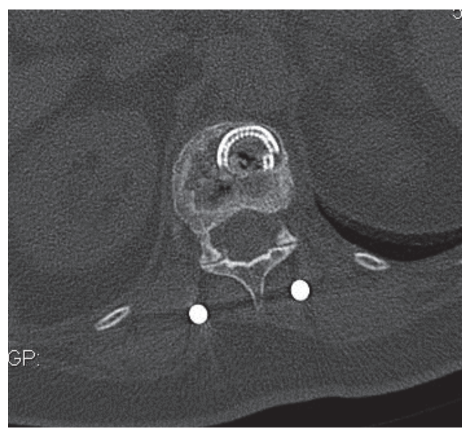
The following roentgenographic parameters were measured at the time of admission and postoperatively: (a) segmental kyphotic deformity (SKD) (defined by the angle formed from the lines drawn on the lower endplate of the



(a) Preoperative CT scan of a 61-year-old woman with an L1 fracture and posttraumatic L1 vertebral body wedging of 20°



(b) Postoperative CT scan of the patient in (a) obtained 27 months postoperatively showing the PEEK implant with Sr-HA in the correct position and a reduction of segmental kyphosis to 11°; Note the resorption of the paste inside the PEEK loops



(c) Postoperative CT scan 12 months after surgery in a 67-year-old woman showing complete resorption of Sr-HA and bone healing around the PEEK implant; no Sr-HA traces are shown inside the PEEK loops

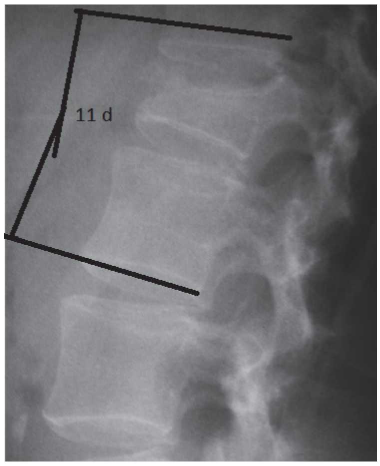
Figure 1

intact vertebra inferior to the fractured vertebra and the upper endplate of the adjacent vertebra superior to the fractured vertebra), (b) anterior vertebral body height ratio (AVBHr), (c) middle vertebral body height ratio (MVBHr), (d) posterior vertebral body height ratio (PVBHr) (vertebral body height ratios are equal to the fractured vertebral body height divided by the average of the vertebral body heights of the adjacent intact vertebrae superior and inferior to the fractured vertebra), (e) refractures, and (f) adjacent or remote vertebral fractures.

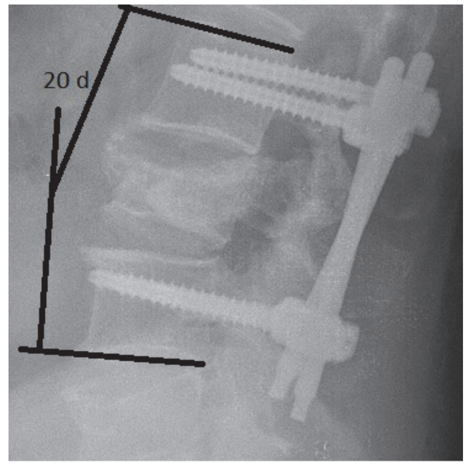
On axial CT scans, the percentages (%) of spinal canal encroachment (SCE) and spinal canal clearance (SCC) (the narrowest anteroposterior spinal canal diameter divided by the average anteroposterior diameter of the two adjacent noninjured vertebrae) were evaluated.

One senior orthopedic spine surgeon and one senior orthopedic radiologist were asked to evaluate the following parameters on axial CT scan slices: cement (Sr-HA or PMMA) leakage and Sr-HA resorption and bone substitution within the cylinder formed by the implanted PEEK loops. Since there is no available method for quantitative or qualitative evaluation of bone cement resorption, the evaluation of Sr-HA resorption and cancellous bone formation (Group A) inside the column constructed by the PEEK loops was rated as present (+) or absent (−) based on different axial CT scan slices taken 12 months postoperatively (Figures 1(a)–1(c)). Patients were encouraged to walk wearing a 3-point fixation brace from the first day following surgery and for a period of 6 weeks.

2.2. Statistical Analysis. Statistical analysis was performed with paired (change of variables in the same group) and unpaired (change of a variable in different groups) t-tests for changes in every radiographic parameter. The kappa value for agreement was used for the radiological evaluation of Sr-HA resorption only, since the digital roentgenograms and



(a) Lateral roentgenogram of a 54-year-old woman who sustained a traumatic L3 A3/AO-type fracture



(b) Lateral roentgenogram of the patient in (a) obtained 27 months postoperatively following Sr-HA injection and short-segment pedicle screw fixation; there is a correction of the preoperative 11° kyphosis to a 20° lordosis and reduction of the L2 endplates

Figure 2

CT scans are highly reliable. The interobserver reliability was measured by the kappa values. Kappa values between 0.61 and 0.80 were considered to indicate "substantial agreement."

2.3. Implant Characteristics. Sr-HA paste is a radiopaque, osteoconductive, and osteocompatible bone substitute that was used in this study, together with the PEEK implant, for vertebral body augmentation in all 15 patients of Group A. Sr-HA consists of highly pure synthetic, fully resorbable, nanocrystalline hydroxyapatite (HA) with strontium (Sr) and water. Sr-HA is gradually resorbed and replaced by bone during the remodeling process, and the strontium-developed drug acts as an effective antiosteoporotic therapy in postmenopausal women with osteoporosis [19, 20].

Previous studies have reported the occurrence of osteogenesis early after the implantation, while the histological integration of Sr-HA in sheep's vertebrae revealed excellent osteogenic and osteoconductive properties. No adverse events (cytotoxicity or hemolysis), rejections, or osteolyses have been recorded [6, 21, 22]. The reported compressive strength of Sr-HA is 40.9 MPa, which is 2 to 9.9 times lower than that of PMMAs (80–396 MPa) and 2–8 times higher than that of cancellous bone (6–24 MPa) [14]. Its bending strength is 31.3 MPa, which is 50% lower than that of PMMAs (67–72 MPa) and 10 times stronger than that of cancellous bone (3 MPa) [12, 14].

3. Results

All patients in both groups were followed up for an average of 28 months (range: 24–33 months).

The *operative time* in both groups averaged 65 minutes (range: 55–80 minutes). The *fluoroscopy exposure time* ranged from 1.05 to 4.2 minutes, with an average time of 1.3 ± 1.14 min, and this was similar in both groups ($P = 0.72$). The *volume of injected liquid* of Sr-HA (Group A) per vertebra averaged 1.5 ml (range: 1-2 ml) and did not differ from PMMA with average volumes of 2 ml (range: 1–2.5 ml) (Group B) ($P = 0.64$).

No significant amount of perioperative *blood loss* was observed in either group. No significant decrease in hemoglobin was observed postoperatively, and no blood transfusion was given to any patient in both groups. The *hospital stay* in both groups averaged 2 days (range: 1–3 days).

Baseline *VAS back pain* scores in both groups improved significantly by 3 months postoperatively ($P < 0.000$). Improvements of VAS scores in Group A averaged 2 ± 3, and the average in Group B was 1.6 ± 2. There was no difference in VAS changes between the two groups ($P = 0.7$). No further significant changes in VAS score were seen in the patients of either group.

The *kappa values* among the two observers after evaluating the roentgenographic and CT parameters ranged from 0.96 to 0.98. The baseline and follow-up radiographic and CT scan parameters values did not differ significantly between the two groups (Table 1, Figures 2(a) and 2(b)).

PMMA leakage without sequelae was observed in one patient in Group B, while no Sr-HA paste leakage was observed in Group A. No loss of correction of SKA, AVBHr, and PVBHr and no change of SCC were measured at the latest observation point (average follow-up of 28 months) in both groups (Table 1). Sr-HA resorption and replacement with vertebral bone were observed by 12 months postoperatively in all the spines of Group A (Figures 1(a), 1(b), and 1(c)). No adjacent or remote new fractures were observed in the latest follow-up (average follow-up of 28 months).

4. Discussion

This preliminary comparative study examined the short- and medium-term efficacy of percutaneous VP with PEEK

TABLE 1: Comparative presentation of radiological changes observed in Group A and Group B preoperatively till the last follow-up.

Parameters	PREOP		GrA/GrB	Postop		GrA/GrB	3 months		GrA/GrB	6 months		GrA/GrB	Last follow-up		GrA/GrB
	GrA	GrB	P value	GrA	GrB	P value	GrA	GrB	P value	GrA	GrB	P value	GrA	GrB	P value
AVBHr	0.59 ± 0.11	0.63 ± 0.14	0.48	0.79 ± 0.12	0.87 ± 0.15	0.22	0.75 ± 0.12	0.86 ± 0.17	0.1	0.7 ± 0.15	0.9 ± 0.20	0.089	0.71 ± 0.16	0.91 ± 0.19	0.09
MVBHr	0.53 ± 0.12	0.68 ± 0.16	**0.054**	0.66 ± 0.08	0.86 ± 0.13	**0.06**	0.73 ± 0.15	0.8 ± 0.20	0.24	0.63 ± 0.2	0.8 ± 0.12	0.21	0.6 ± 0.18	0.82 ± 0.13	0.23
PVBHr	0.95 ± 0.15	0.97 ± 0.18	0.77	0.97 ± 0.07	1 ± 0.09	0.069	1 ± 0.12	1 ± 0.11	0.13	0.98 ± 0.13	1 ± 0.18	0.4	1 ± 12	1.1 ± 0.17	0.45
+SKA	14.7 ± 8.7	13.9 ± 8	0.81	8.6 ± 7	9 ± 4	0.88	13 ± 8	10 ± 6	0.40	10 ± 6	12 ± 8	0.65	12 ± 5	14 ± 9.8	0.66
SCE (%)	22 ± 17	26 ± 19	0.46							15 ± 13*	10 ± 15*	0.49			

*SCE values on CT scan 12 months following surgery. GrA: Group A; GrB: Group B; AVBHr: anterior vertebral body height ratio; MVBHr: middle vertebral body height ratio; PVBHr: posterior vertebral body height ratio; SCE: spinal canal encroachment. +SKA in Cobb degrees.

and Sr-HA or PMMA plus short-segment pedicle screw fixation for single fresh A2- and A3/AO-type thoracolumbar fractures. We also evaluated the amount of Sr-HA resorption and substitution with cancellous bone. All three hypotheses in this study were confirmed: (1) Sr-HA and PMMA equally restored the fractured thoracolumbar vertebral body angulation and heights, (2) bone cement leakage in VP with Sr-HA was less than that with PMMA, and (3) Sr-HA paste was resorbed and replaced by cancellous bone.

Previous clinical studies showed that percutaneous VP with PEEK and low-viscosity PMMA for osteoporotic vertebral body fractures in elderly patients exhibited PMMA containment [13, 16]. However, because of the exothermic reaction and heat released during the PMMA hardening process, an active membrane is created around the PMMA cement, which is considered to be a potential disadvantage of PMMA osseointegration [3, 23, 24]. It seems that osseointegration provides a critical advantage of Sr-HA over PMMA. This advantage of Sr-HA may result in better long-term outcomes and fewer potential adverse reactions than those reported with PMMA, in cemented hip and knee arthroplasties. Previous studies reported no adverse reactions associated with Sr-HA use, probably because of the nontoxic nature of bisphenol-A bis(2-hydroxypropyl)methacrylate (BISGMA) and the lower setting temperature of Sr-HA [6, 12, 14].

HA is a biocompatible and osteoconductive material. The mechanism of formation and strengthening of the bone-HA interface has been studied using high-resolution transmission electron microscopy and energy-dispersive X-ray analysis [25]. It was suggested that the transition of crystalline to amorphous HA is the first critical step in bone-to-implant bonding. The osseointegration of an implant as a function of the biological response to HA can be significantly enhanced by pharmaceutical agents [26, 27]. It was found that apatites obtained by partial substitution of Ca^{++} by Sr yield higher solubility compared to pure HA [28]. Both Sr and Ca^{++} have common chemical properties, while Sr is characterized as "a bone seeking element" having a similar charge/size ratio to Ca^{++}.

A previous study showed an increase in bone mass following oral intake of Sr-HA for osteoporosis [9]. Sr is beneficial for bone health in postmenopausal osteoporotic women, because it assists in the replication of preosteoblastic cells promoting bone formation [29] and, to a lesser extent, decreases bone resorption *in vivo* [30].

Oral administration of Sr salts results in adsorption of Sr ions on the apatite surface or in the substitution of Ca^{++} ions in the apatite crystal lattice at low ion exchange rates. Only about 10% of the Ca^{++} ions are substituted by Sr ions [31]. The procedure of ion exchange is more profoundly realized in new bone during remodeling. There is some controversy regarding the beneficial effects of Sr on bone because it is dose-dependent, and although low doses stimulate bone formation, high doses have deleterious effects on bone mineralization [9, 32–34]. Increased attention has been paid to the repair of osteoporotic fractures by Sr-modified bioceramics with improved osseointegration capabilities. Moreover, biocompatible Sr-doped HAs enhance the peri-implant bone formation more efficiently than the administered strontium [35].

Recently, Li et al. [36] published a thought-provoking study of doped hydroxyapatite (Sr-HA) in ovariectomized rats, comparing HA and Sr-HA. In this study, Li et al. [36] clearly showed that Sr-HA is a promising material for bone tissue engineering, because it promotes osteogenesis and improves the trabecular microarchitecture under osteoporotic conditions. The osteoconductive properties of different Sr-doped biocomposites have been investigated in numerous bone defects [37, 38]. It has been reported that the implantation of Sr-containing HA materials promotes bone repair and healing in both normal [39] and ovariectomized [36, 40] animals.

A previous study regarding the use of VP for osteoporotic single spine fractures revealed that Sr-HA is incorporated during the bone remodeling as early as 3 to 6 months after implantation [5]. In an animal research study, newly formed bone grew onto the Sr-HA by 4 months following surgery [15]. Complete Sr-HA resorption was documented on CT scans 12 months postoperatively in all 15 patients of Group A, justifying the previously mentioned study. This means that the Sr-HA ingredients (hydroxyapatite and strontium) are resorbed without interference during the vertebral bone healing process and probably induce osteogenesis.

Another advantage of the use of bioactive cements is their lower leakage rate [5, 13]. A leakage rate of 22% was reported with the use of PMMA in fresh thoracolumbar vertebral body fractures, whereas the leakage rate with calcium phosphate was 15% [13]. A clinical study reporting on the use of Sr-HA in VP for the augmentation of single osteoporotic thoracolumbar fractures revealed maintenance of the vertebral body height with only 3 (13%) cases of slight Sr-HA leakage into the spinal canal, but none of the patients developed any neurologic sequela [5]. In the present study, the leakage rate with PEEK was 7.5% when using PMMA and 0% when using Sr-HA.

The addition of pedicle screws together with the PEEK implant secured the vertebral body stiffness against compression and rotational forces acting across the thoracolumbar spine immediately following surgery and thus, at least theoretically, enhanced the process of bone healing and new bone formation. There were no reactions, either local or systemic, to Sr-HA injections in any of the patients.

In contrast to Sr-HA, which is a resorbable bioactive bone cement, PMMA is not resorbable. Taking into consideration the extensive experience gained in clinical practice with PMMA and its low cost, efforts have been made recently to improve the bioactivity of PMMA [41]. Researchers have attempted to improve PMMA bioactivity and osseointegration by incorporating Sr-containing borate bioactive glass (SrBG) as a reinforcement phase and bioactive filler for the PMMA cement [41]. The prepared SrBG/PMMA composite cements showed evidence of significantly decreased polymerization temperatures, when compared with PMMA alone. The composite also retained the properties of appropriate setting times and great mechanical strength. The bioactivity of the SrBG/PMMA composite cements was confirmed *in vitro*, as evidenced by ion release (Ca^{+2} P, B, and Sr) from

SrBG particles. It has been demonstrated *in vitro* that SrBG incorporation may promote adhesion, migration, proliferation, and collagen secretion by cells. Consequently, the SrBG/PMMA composite cement may be a better alternative to cement made from PMMA alone, in clinical applications, and it has promising applications in minimally invasive orthopedic surgery.

A limitation of this study is that it is a pilot study, with a small ($n = 30$) number of patients. Further, it has limited power, since the results may be subject to a Type II error.

5. Conclusions

Based on the results of the present preliminary study and taking into consideration the small number of individuals included, the authors recommend using Sr-HA bioactive bone cement instead of PMMA, supplemented by short pedicle screw construction, in adults with osteoporotic and fresh traumatic thoracolumbar fractures. However, further studies, with a greater number of patients and longer follow-up, are needed.

Ethical Approval

All the authors certified that the study was performed in accordance with the ethical standards in the 1964 Declaration of Helsinki; therefore, the ethical committee approved the study.

Disclosure

An earlier version of this work was presented as a poster at the Global Spine Congress (GSC), 6th Annual Meeting for AOSpine 2017 [42].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Review Article

Pathology and Treatment of Traumatic Cervical Spine Syndrome: Whiplash Injury

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Traumatic cervical syndrome comprises the various symptoms that occur as a result of external force such as that of a traffic accident. In 1995, the Quebec Task Force on whiplash-associated disorders (WAD) formulated the Quebec classification, with accompanying clinical practice guidelines. These guidelines were in accordance with the stated clinical isolated or combined symptoms of the syndrome: neck pain, headaches, dizziness, numbness of head or face, eye pain, vision loss, double vision, tinnitus, hearing loss, nausea, and numbness and/or weakness of extremities. In recent years, cerebrospinal fluid hypovolemia or fibromyalgia has been recognized as a major notable cause of a variety of symptoms, although many clinical questions remain regarding the pathology of this syndrome. Therefore, its diagnosis and treatment should be conducted extremely carefully. While the Quebec classification and its guidelines are very useful for the normalization and standardization of symptoms of traumatic cervical syndrome, in the future, we would like to see the emergence of new guidelines that better address the diversity of this disease.

1. Introduction

Traumatic cervical syndrome is defined as the "biological and neurological consequences for the cervical spine and nervous system caused by neck trauma, and is a syndrome comprising various symptoms of the motor and nervous system [1] but also mental, neurological, as well as otological and visual balance dysfunction" [2, 3] (Table 1). The symptoms can include minor neck trauma without the so-called "whip" movement of the neck. "Whiplash injury," which has been traditionally diagnosed after a traffic injury, is pathologically incorrect and should not be used as part of clinical language, because it may cause various misunderstandings among communities and patients. Most injuries occur during a rear-end auto accident, but the injury can also result from a sports accident, physical abuse, or other trauma. Also Ferrari [4] noticed that whiplash is an example of illness induced by society, in general, and by physicians in particular. These symptoms may appear even in the absence of any visible injuries.

The report of the Quebec Task Force on whiplash-associated disorders in 1995 classified whiplash-associated disorders (WAD) into five grades based on symptoms and severity [2]. In this manuscript, we discuss the clinical signs of traumatic cervical syndrome which conform to the Quebec classification.

2. Quebec Classification

The Quebec classification includes neck symptoms and a range of neurological problems, as well as spine fractures or dislocations, and it is divided into 5 grades from 0 to IV [2] (Tables 2 and 3). Grades 0, I, and II correspond to the so-called "whiplash injury," and grades III and IV are classified as traumatic cervical spinal cord injury. Symptoms such as

Table 1: Neurological symptoms after whiplash injury [1].

Headaches	Migraine-type headache Tension-type headache Cervicogenic-type headache Temporomandibular joint derangement Greater occipital neuralgia Third occipital headache
Cognitive and psychological symptoms	Memory, attention, or concentration impairment Sleep disturbance Psychiatric disorders: anxiety, depression, phobic travel, anxiety, and posttraumatic stress disorder
Dizziness	Vestibular dysfunction Cervical origin Brainstem dysfunction
Visual symptoms	Blurred vision Reduced visual field Photophobia Disordered fusion Reading and driving difficulties Reduced accommodation
Paresthesias	Trigger points Brachial plexopathy Cervical radiculopathy Spinal cord compression
Weakness	Brachial plexopathy Cervical radiculopathy Spinal cord compression
Rare symptoms	Torticollis Tremor Transient global amnesia Hypoglossal nerve palsy Superior laryngeal nerve paralysis Cervical epidural hematoma Brainstem infarct Internal carotid and vertebral artery dissection Symptomatic Chiari malformation

Table 2: Clinical classification on whiplash-associated disorders proposed by the Quebec Task Force [2].

Grade	Clinical presentation
0	No complaint about neck pain No physical signs
I	Neck complaint of pain, stiffness, or tenderness No physical signs
II	Neck complaint Musculoskeletal signs including Decreased range of movement Point tenderness
II	Neck complaint Musculoskeletal signs Neurological signs including Decreased or absent deep tendon reflexes Muscle weakness Sensory deficits
IV	Neck complaint and fracture or dislocation

dizziness, tinnitus, headache, memory loss, swallowing, and temporomandibular joint pain can appear in any grade.

3. Clinical Symptoms

3.1. Neck Pain. Although symptoms of traumatic cervical syndrome vary from patient to patient (Table 1), neck pain and cervical discomfort are typical symptoms [1]. Deans et al. [6] reported that neck pain occurs in 65% of patients within 6 hours, 93% within 24 hours, and 100% within 72 hours after neck injury. Many factors can influence the extent and location of the injury, such as traffic accident specifics (speed, direction, and safety equipment) and the state of the victim's cervical spine. In addition to the constructional elements of the cervical spine such as muscles, intervertebral discs, and facet joints, the injury may be caused by neural elements including the spinal dorsal root ganglion, vertebral artery, and the sympathetic nervous system. Typical clinical characteristics of the injury include the patient not complaining of neck pain immediately after the accident, but then complaining of neck pain a few hours later or the next day. This time lag can be explained by synovitis of the facet joints, where the synovial tissue involved in the facet joint has been damaged by nonphysiological behavior during a collision, which may induce synovitis of the facet joint after several hours, leading to neck pain and a limited range of motion [7].

In general, traumatic cervical spine syndrome is not protracted, and many patients recover from the symptoms within a few weeks or months. However, some reports suggest that neck pain and headaches continue for several years in 20–40% of patients, with 3-4% of patients unable to return to work [8]. Radanov et al. [9] reported that 97% of chronic traumatic cervical syndrome patients have neck pain. Clinical conditions are usually complicated and enigmatic when the injury is chronic, while the potential exists for abnormally prolonged arthritis of the synovial membrane, cervical nerve root irritation of the posterior branches, and vestibular reflex abnormalities due to vestibular dysfunction, neck muscle tension, or fibromyalgia (see below), but details of the pathology remain unclear.

3.2. Headache. Headaches present as chronic symptoms in 70% of patients [8]. According to the headache classification proposed by the International Headache Society (2nd edition) [10] (Section 3.2.1), a cervicogenic headache is defined as a headache resulting from disorders of the cervical spine. The diagnostic criteria following the blockade of a cervical

Table 3: Clinical spectrum of whiplash-associated disorders as proposed by the Quebec Task Force [2].

Grade	Presumed pathology	Clinical presentation
I	Microscopic or multimicroscopic lesion Lesion is not serious enough to cause muscle spasm	Usually presents to a doctor more than 24 h after trauma
II	Neck sprain and bleeding around soft tissue (articular capsules, ligaments, tendons, and muscles) Muscle spasm secondary to soft tissue injury	Usually presents to a doctor in the first 24 h after trauma Nonspecific radiation to the head, face, occipital region, shoulder, and arm form soft tissues injuries Neck pain with limited range of motion due to muscle spasm
III	Injuries to neurologic system by mechanical injury or by irritation secondary to bleeding or inflammation	Presents to a doctor usually within a few hours after the trauma Limited range of motion combined with neurologic symptoms and signs

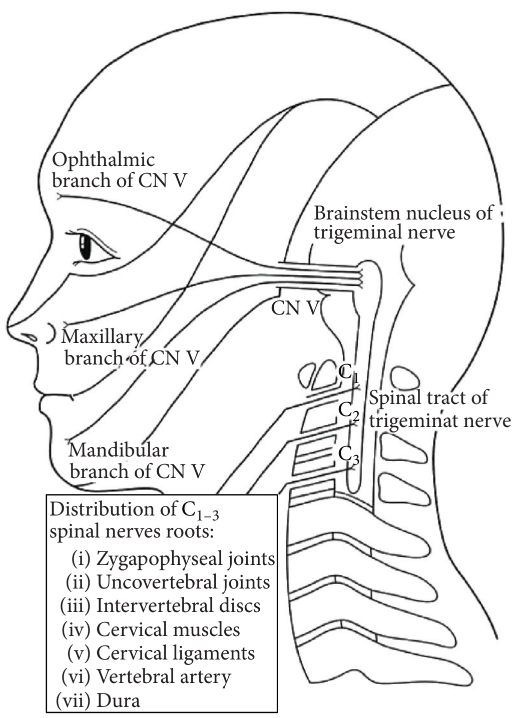

Figure 1: Schema of connection between upper spinal nerve roots and trigeminal nerve [5].

structure include referred pain from a source in the neck, perceived in the head and/or face, and evidence of a disorder or lesion within the cervical spine or soft tissues of the neck.

Some of the proposed trigger mechanisms of a cervicogenic headache are compression or inflammation of the C2 nerve root; referred pain of the first branch of the trigeminal nerve from C2 nerve root irritation trough anastomosis; emerging pain in the trigeminal nerve area caused by stimulation of the upper spinal nerve roots from the anatomical connection between the spinal trigeminal nucleus and dorsal horn at the C2-3 spinal level [5] (Figure 1); a tension headache due to entrapment of the occipital nerve after pericranial muscles constrict from cervical muscle strain or spasm. Many cervicogenic headaches are caused by movement of the neck, and pain is usually located in the occipital region, with persistent pain gradually increasing on an elapsed chronic course. Psychological factors such as fatigue, lack of sleep, stress, and depression are reported to influence cervicogenic headaches [7].

3.2.1. Diagnostic Criteria of Cervicogenic Headache [8]

(A) Pain, referred from a source in the neck and perceived in one or more regions of the head and/or face, fulfilling criteria (C) and (D)

(B) Clinical, laboratory, and/or imaging evidence of a disorder or lesion within the cervical spine or soft tissues of the neck known to be, or generally accepted as, a valid cause of headache (Tumors, fractures, infections, and rheumatoid arthritis of the upper cervical spine have not been validated formally as causes of headache but are nevertheless accepted as valid causes when demonstrated to be so in individual cases. Cervical spondylosis and osteochondritis are not accepted as valid causes for the fulfillment of criterion (B). When myofascial tender spots are the cause, the headache should be coded under 2, *tension-type headache.*)

(C) Evidence that the pain can be attributed to the neck disorder or lesion based on at least one of the following:

(1) Demonstration of clinical signs that implicate a source of pain in the neck (Clinical signs acceptable for criterion C1 must have demonstrated reliability and validity. The future task is the identification of such reliable and valid operational tests. Clinical features such as neck pain, focal neck tenderness, history of neck trauma, mechanical exacerbation of pain, unilaterality, coexisting shoulder pain, reduced range

of motion in the neck, nuchal onset, nausea, vomiting, and photophobia are not unique to a cervicogenic headache. These may be features of a cervicogenic headache, but they do not define the relationship between the disorder and the source of the headache.)

(2) Abolition of headache following diagnostic blockade of a cervical structure or its nerve supply using placebo or other adequate controls (Abolition of headache means complete relief of headache, indicated by a score of zero on a visual analogue scale (VAS). Nevertheless, acceptable as fulfilling criterion C2 is ≥90% reduction in pain to a level of <5 on a 100-point VAS.)

(D) Pain resolves within 3 months after successful treatment of the causative disorder or lesion

3.3. Vertigo. There are two types of dizziness: vertigo and planktonic, and physicians should be careful in their diagnosis of the symptoms, because brain-stem bleeding sometimes manifests itself as vertigo, when in fact it is mostly caused by an inner ear disorder. Planktonic dizziness is caused by craniocervical disorder (Chiari malformation, spinal cord tumor, etc.) or failure of the input system regarding the spinal cord. Dizziness originating from the cervical spine is collectively known as cervical vertigo, and it may be caused by circulatory failure of the vertebral artery, proprioceptor dysfunction of the cervical spine (nerve root or spinal cord disorders at C1—3), or cervical sympathetic nervous system disorders (Barré-Lieou syndrome). Hinoki [11] proposed a hypothesis in which the hypothalamus plays a fundamental role in explaining vertigo after injury. They reported that autonomic reflexes in patients with whiplash injury can be explained as being not only due to overexcitation of the cervical sympathetic nerves, but also due to the cervical and lumbar proprioceptors in producing vertigo.

3.4. Barré-Lieou Syndrome. Symptoms of Barré-Lieou syndrome include headache, dizziness, and other cervical sympathetic nervous system disorders, some of which can be classified as traumatic. Hypertension of the cervical sympathetic nerves and vertebral arterial circulatory disorders, stem failure, peripheral vestibular disorders, and psychogenic problems are caused mainly by stress. These symptoms are known as posterior cervical sympathetic syndrome, previously recognized as a syndrome associated with chronic cervical disease, but recently it often comprises a convenient but false diagnosis for atypical symptoms [12].

3.5. Numbness in Head and Face. Disruption of the trigeminal spinal nucleus, which conveys superficial facial perception along the C2-3 spinal level (see above), can lead to numbness or loss of sensation around the face in an “onion skin” distribution area, followed by a spinal cord lesion at the upper cervical spine [6].

3.6. Eye Symptoms. There are reports that eye symptoms emerge in 35% of traumatic cervical syndrome patients [13]. Eye pain due to trigeminal nerve stimulation, eye movement disorder (double vision) caused by oculomotor nerve disorders, visual deficit due to optic nerve disorders, and blepharoptosis due to sympathetic nervous system disorders are present.

3.7. Nausea and Vomiting. It is reported that nausea and vomiting are found in 17 to 29% of patients. Almost all cases have neck pain complications. Subsequently these symptoms persist for more than 6 months in 33% of patients [7].

3.8. Limb Symptoms. Numbness or muscle weakness of the upper extremities may appear as nerve root or spinal cord symptoms, although limb symptoms of traumatic cervical syndrome often do not produce any findings in imaging studies. Because there are few available laboratory procedures for these patients, appropriate treatment based on their pathophysiology is difficult to administer.

De Reuck [14] reported the usefulness of investigating motor evoked potentials (MEPs) in patients who had been suffering from grade II WAD for more than 6 months. They found that 13 patients had prolonged central (CMCT) and/or peripheral motor conduction times (PMCT) compared to normal values, and they recommended that MEP examination be performed in all patients with persistent pain even in the absence of objective neurological signs and nonsignificant changes on imaging. In our study, we also used electrophysiological examination using MEPs following transcranial magnetic stimulation for traumatic cervical syndrome patients, and we found significant elongation in PMCT and/or distal latencies following nerve stimulation at the cervical nerve root or Erb’s point in 4 out of 11 patients who had limb symptoms without significant imaging abnormalities but with no obvious CMCT abnormalities [15]. These results may indicate potential nerve disorder in the cervical nerve root or brachial plexus in patients with traumatic cervical syndrome, even in those who develop symptoms of malaise without obvious muscle atrophy or electromyographic changes.

3.9. Other. The mechanisms of the following symptoms are unclear: ringing in the ears, hearing loss, insomnia, loss of concentration, fatigability, fever, memory loss, temporomandibular joint pain, and anginal-like chest pain (cervical angina).

4. CSF Hypovolemia

In Japan, some physicians have insisted that the cause of CSF hypovolemia is traumatic CSF leak, and they call this syndrome traumatic CSF hypovolemia [16]. CSF hypovolemia syndrome exhibits a variety of symptoms such as neck pain, visual deficit, double vision, dizziness, nausea, vomiting, ringing in the ears, hearing loss, and headaches. These symptoms resemble those of a whiplash injury, and some of them occur sporadically as traumatic cervical syndrome [17–19]. The diagnostic criteria of traumatic CSF leakage is defined as follows: (1) early vesicular radioisotope cisternography (RIC) accumulation (EVA); (2) promoted radioisotope (RI)

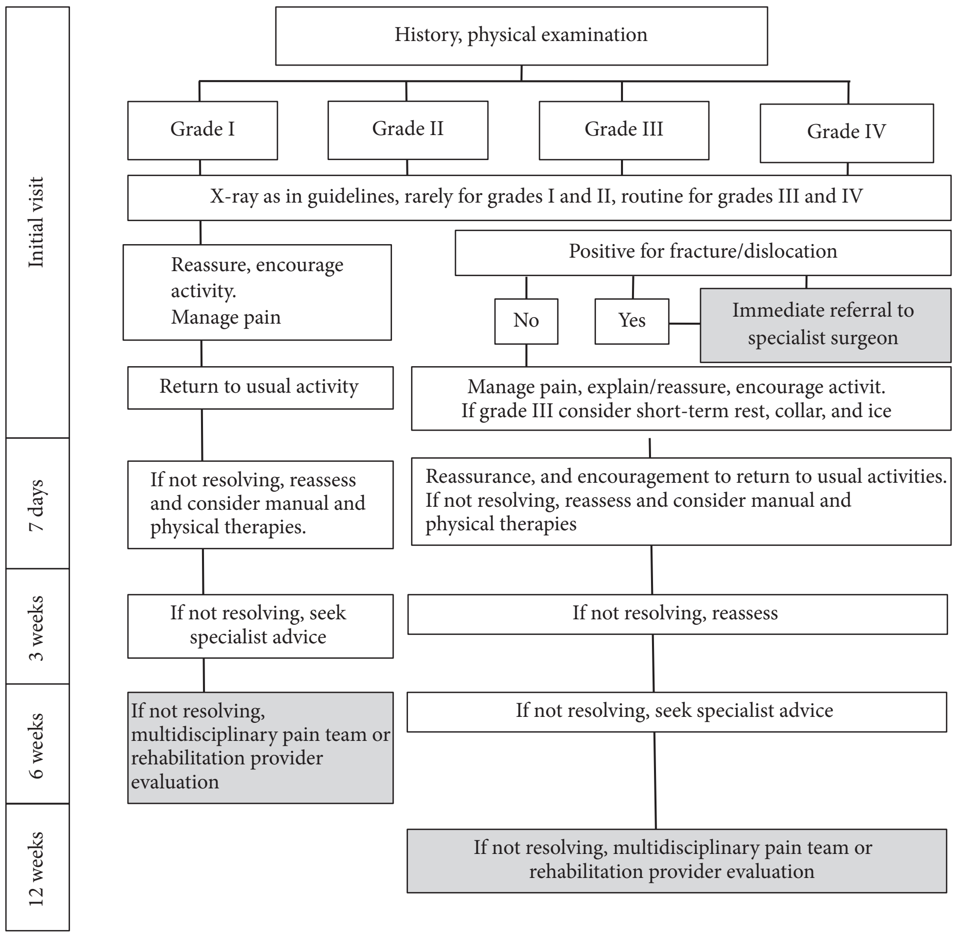

Figure 2: Clinical practice guidelines by Quebec Task Force on whiplash-associated disorders [2].

clearance from the spinal cavity; (3) presence of abnormal paraspinal RI accumulation (PSA) [20]. However, Hashizume et al. [21] reported that traumatic CSF leak was not observed on CT myelography findings in patients with WAD, in whom CSF leak was suspected when comparing the RIC. An epidural blood patch (EBP) is the therapy of choice in patients with chronic WAD with a suspected CSF leak. Treatment for traumatic cervical spine syndrome should be uniform and logically based on medical science, and invasive treatment such as EBP should be carefully performed only in selected patients. The association of a CSF leak with chronic WAD has never been established, although its symptoms may be reduced following treatment.

5. Fibromyalgia

Fibromyalgia is defined as a neurosensory disorder characterized by widespread muscle pain, joint stiffness, and fatigue, and there are almost no inflammatory findings or abnormalities which indicate organic disorders such as bone and joint diseases, neurodegenerative diseases, rheumatic diseases, or malignant tumors. Other common symptoms of fibromyalgia present with psychosomatic characteristics, such as irritability, sleep disorders, anxiety, depression, and the onset of this disease, are seen predominantly in women in their fifties.

Fibromyalgia is reported to occur as a result of cervical spine injury in 21.6% of patients [22]. Ferrari [23] prospectively examined 268 patients and he found 2 cases (0.8%) of fibromyalgia after acute whiplash injury. Although the etiology and development processes may relate to mental fatigue or physical trauma based on genetic predisposition, the relationship between spine injury and fibromyalgia remains unclear.

6. Clinical Practice for Quebec Guidelines

Clinical practice guidelines were established by the Quebec Task Force on whiplash-associated disorders [2] (Figure 2), to standardize the treatment and its duration based on the severity of symptoms. The final treatment evaluation regarding soft tissue repair is determined at 12 weeks after injury. However, as mentioned above, traumatic cervical syndrome has symptoms across diverse fields such as otolaryngology, neurology, neurosurgery, and internal medicine, as well as orthopaedic symptoms, and they overlap (functional anatomic factors), vary in duration (a time factor), and depend on the biological or social situation of the patient (individual factors). For treatment of WAD, clinicians should realise that expression of clinical symptoms is implicated in biopsychosocial model. WAD according to the Quebec classification can range from a muscle sprain to spinal cord contusions to a fractured vertebra. The latter two are rarer and can easily be detected. But, for the majority of cases, there are considerable cases who have pain with no visible cause. Therefore, the Quebec guidelines may not be applicable for all patients with traumatic cervical syndrome. Although the Quebec classification and its guidelines are very useful for standardization of the symptoms of traumatic cervical syndrome, more comprehensive guidelines are necessary to enable more accurate treatment responses to this diverse disease.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Review Article

Posttraumatic Spinal Cord Injury without Radiographic Abnormality

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"Spinal Cord Injury without Radiographic Abnormality" (SCIWORA) is a term that denotes objective clinical signs of posttraumatic spinal cord injury without evidence of fracture or malalignment on plain radiographs and computed tomography (CT) of the spine. SCIWORA is most commonly seen in children with a predilection for the cervical spinal cord due to the increased mobility of the cervical spine, the inherent ligamentous laxity, and the large head-to-body ratio during childhood. However, SCIWORA can also be seen in adults and, in rare cases, the thoracolumbar spinal cord can be affected too. Magnetic resonance imaging (MRI) has become a valuable diagnostic tool in patients with SCIWORA because of its superior ability to identify soft tissue lesions such as cord edema, hematomas and transections, and discoligamentous injuries that may not be visualized in plain radiographs and CT. The mainstay of treatment in patients with SCIWORA is nonoperative management including steroid therapy, immobilization, and avoidance of activities that may increase the risk of exacerbation or recurrent injury. Although the role of operative treatment in SCIWORA can be controversial, surgical alternatives such as decompression and fusion should be considered in selected patients with clinical and MRI evidence of persistent spinal cord compression and instability.

1. Introduction

The acronym SCIWORA (Spinal Cord Injury without Radiographic Abnormality) was first defined in 1982 by Pang and Wilberger Jr. in a series of 24 children who suffered traumatic myelopathy with no radiographic evidence of fractures, dislocations, or malalignment of the spine [1]. Pang and Pollack described SCIWORA as a syndrome in which there are clinical signs of traumatic spinal cord injury (SCI) without overt traumatic vertebral column disruption as displayed by spine X-rays, computed tomographic (CT) scans, myelograms, and dynamic flexion/extension X-rays [2]. The first human magnetic resonance imaging (MRI) scan was done in 1977, and distinctive MRI signal patterns of acute SCI were first described in 1987 [3, 4]. Hence, the original report from Pang and Wilberger Jr. that introduced SCIWORA into medical literature did not include MRI in the definition of this syndrome; Pang acknowledged the diagnostic potential of MRI in patients with SCIWORA two decades later [5]. It might be sensible to ask, "Would SCIWORA still exist if MRI was readily available for use in acute SCI only a few years earlier?" The answer would probably be "Yes," since MRI is never the first-line imaging modality in the setting of acute spinal trauma. Plain X-rays and CT are almost invariably performed before MRI, since MRI scans require more time, space, and patient transfer that might not be practical in emergency management of trauma patients.

SCIWORA is more commonly seen in the pediatric age group than in adults and involves the cervical spine more frequently than the thoracolumbar spine. The incidences have been reported between 13 to 19% and 10 to 12% of spinal injuries in children and adults, respectively [6–9]. SCIWORA is far more common in males than females [6, 8–10]. In a systematic review, Carroll et al. [10] documented that, of 368 pediatric patients with SCIWORA, approximately 68.5% were male, and 31.5% were female. Cervical spine was involved in 87% of the patients; thoracic spine was involved in 9.5%; lumbar spine was involved in 1.5%; and in 2%, the SCI spanned the cervical and thoracic levels. Evidence from the adult population indicating that thoracolumbar spine can also be involved with SCIWORA is limited to occasional case reports [11, 12]. The reasons for increased frequency of SCIWORA in the pediatric age group with a predilection for the cervical spinal cord include the large head-to-body ratio, increased mobility of the cervical spine, inherent ligamentous laxity, immaturity of neck musculature, incomplete ossification of the vertebrae, and shallow angulation of facet joints during childhood [2, 5, 12]. Interestingly, several studies showed that the upper cervical spine was more susceptible to SCIWORA in younger children than in older children, where the lower cervical spine is more commonly affected [2, 10, 13]. This finding is supported by the fact that the fulcrum of movement is at the upper levels of the cervical spine (between C2 and C4) in younger children and shifts to lower levels (C5-C6) in adolescents and adults [14, 15]. It is conceivable that SCIWORA is seen less frequently in adults as a result of age-related changes in bone morphology and a decrease in ligamentous laxity. Furthermore, the thoracic spine has a more stable and stiff structure compared to the cervical spine due to the surrounding rib cage and costovertebral articulations. Similarly, both the thoracic and lumbar spine have larger bony surfaces that increase axial loading capacity and stability [12].

2. Pathophysiology

Several mechanisms have been proposed to cause SCIWORA including spinal cord traction injury due to hyperflexion, extrinsic cord damage from hyperextension, and parenchymal cord damage resulting from edema or vascular injury [12]. The two-hit hypothesis is one of the possible pathophysiological explanations for delayed cord damage in patients with SCIWORA. After the primary injury from direct impact, a subsequent secondary insult to spinal cord parenchyma from complex cellular-level reactions to the primary injury can worsen the clinical picture [18]. Traumatic SCI may cause increased Na^+ influx into the cells through voltage-gated channels, which may lead to increased H^+ influx and intracellular acidosis through the activation of the Na^+/H^+ exchanger in an attempt by the cell to pump out accumulating intracellular Na^+ [19]. Likewise, increased Na^+ influx after SCI may cause reversal of Na^+/Ca^{++} exchanger that results in an increase in Na^+ extrusion and intracellular Ca^{++} accumulation with apoptosis of the neurons [18, 19]. These changes trigger intracellular events such as free radical-mediated cell damage, lipid peroxidation, and activation of membrane lipases. Consequently, a cascade of secondary inflammatory reactions, edema, and ischemia resulting in further spinal cord parenchymal insult can occur [18, 19].

3. Mechanism of Injury

The most common causes of injury in patients with SCIWORA are sports injuries, motor vehicle collisions, falls, and abuse [2, 10, 13]. In a series of 297 children who suffered from SCIWORA, Knox [13] demonstrated age-related variations in the mechanism of injury. Between 0 to 10 years, the most common cause of injury was found to be motor vehicle collisions (38–40%). However, sports injuries were the most common injury mechanism in children between 11 and 17 years of age (57%). In adult patients with SCIWORA, falls appear to be the most common mechanism of injury. Como et al. [20] reported that, of the 24 adult patients with SCIWORA, 67% had a mechanism of fall. In another study from Sharma et al. [9] of 12 adult SCIWORA patients, five (42%) were injured in motor vehicle accidents, and four (33%) fell from height. The difference between the two studies in terms of the most common mechanism of injury can be attributed to the difference in the number of patients included in each study (24 versus 12 patients, resp.). The literature includes sporadic publications reporting on thoracic SCIWORA cases in adults following motor vehicle accidents [11, 12]. Despite insufficient evidence, this may indicate the severity of the injury mechanism required to cause SCIWORA in the biomechanically more stable thoracic spine.

4. Diagnostic Evaluation

After the initial management in the field, diagnostic evaluation of patients with presumed SCI should start with a detailed history which can be possibly taken from eyewitnesses to determine the mechanism of injury [5]. More often than not, there are associated injuries of the head, thorax, abdomen, face, vasculature, pelvis, and the extremities. In a study of nationwide pediatric admissions, Knox [13] reported that 87% of patients with SCIWORA had associated injuries, and head trauma was the most common injury (between 28 to 64%), followed by orthopaedic injuries (10%), facial injuries (9%), thoracic injuries (9%), and gastrointestinal injuries (4%). It is imperative to detect and address these injuries, which can also provide clues to the mechanism of injury [5].

4.1. Clinical Findings. Clinical examination focusing on neurological findings may reveal a broad range of neurological deficits. Although clinical signs and symptoms can be observed from the moment of injury, neurological deficits may only become apparent several days after the injury due to second-hit phenomenon, edema, or a developing hematoma around the cord [21].

Table 1: Summarized descriptions of ASIA Impairment Scale (AIS) Grades A, B, C, D, and E. Please note that only patients with an initial SCI and neurological findings receive an AIS grade. *(Source: with permission from American Spinal Injury Association: International Standards for Neurological Classification of Spinal Cord Injury.)*

American Spinal Injury Association (ASIA) Impairment Scale (AIS)		
Grade		Description
A	Complete	No sensory or motor function is preserved in the sacral segments S4-5
B	Sensory incomplete	Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-5 AND no motor function is preserved more than three levels below the motor level on either side of the body
C	Motor incomplete	Motor function is preserved at the most caudal sacral segments for voluntary anal contraction OR the patient meets the criteria for sensory incomplete status
D	Motor incomplete	Motor incomplete status as defined above, with at least half (half or more) of key muscle functions below the single NLI having a muscle grade ≥ 3
E	Normal	If sensation and motor function are graded as normal in all segments and the patient had prior deficits, then the AIS grade is E

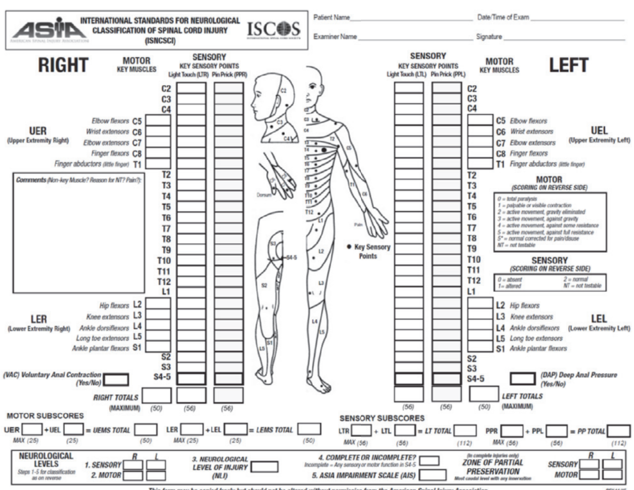


Figure 1: American Spinal Injury Association (ASIA) Injury Scale. *(Source: with permission from American Spinal Injury Association: International Standards for Neurological Classification of Spinal Cord Injury.)*

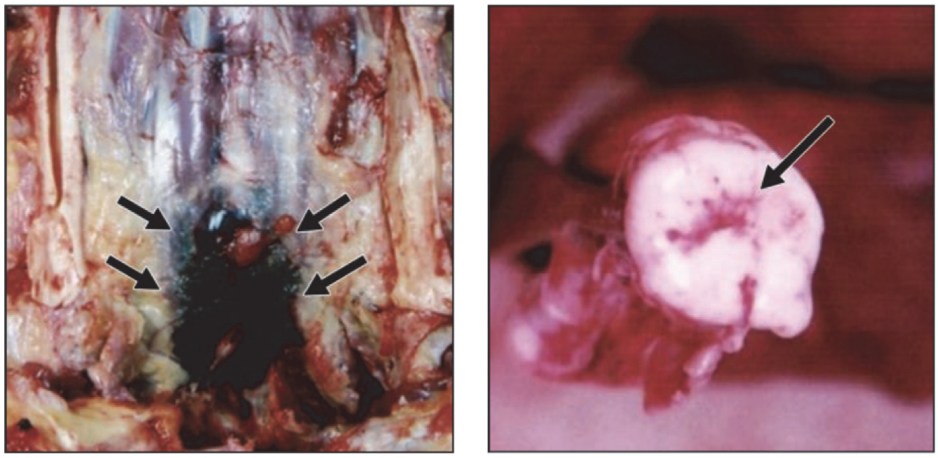
A thorough neurological examination immediately after the injury may indicate the level of SCI and help to monitor the progress of patients at later stages of their management. It is advisable to use one of the SCI scales, such as the American Spinal Cord Injury Association (ASIA) scale (Figure 1), and report the neurological examination findings as ASIA Impairment Scale (AIS) grades (Table 1) [22]. Published reports indicate that patients with SCIWORA may present with a wide range of neurological findings, including para/hemiparesis/plegia, paresthesia, changes in tendon reflexes, loss of bladder and bowel function, signs of anterior/central/posterior cord or Brown-Séquard syndrome in addition to local pain, sensitivity, abrasions, and bruising around the vertebral column [2, 11, 12, 17, 23].

In a retrospective case series from Martinez-Perez et al. [8] that included 48 adult patients diagnosed with SCIWORA, two patients had complete SCI with AIS grade A; five patients were documented as AIS grade B; 15 patients had AIS grade C; and 26 patients had AIS grade D SCI at admission. Neurological assessment of the patients at one-year follow-up revealed that neither of the two patients with complete SCI showed improvement after admission. All but eight patients (two grade B, two grade C, and 6 grade D) with incomplete SCI had improvement of at least one grade on AIS at one-year follow-up [8].

It should be kept in mind that neurological findings in SCIWORA patients may not always be prominent, and there may be fluctuations in severity.

4.2. Plain Radiographs and CT. In all patients with traumatic SCI, anteroposterior (AP), lateral (LAT), and odontoid views of the cervical spine are obtained. Depending on the level of injury, AP and LAT views of the thoracic and lumbar spine are added. If plain films do not reveal any abnormalities, then thin-section CT scans with coronal and sagittal three-dimensional (3D) reconstructions are performed. By definition, neither plain X-rays nor CT will reveal any signs of vertebral column fractures, dislocations, or malalignment in patients with SCIWORA syndrome despite the neurological findings of traumatic SCI in clinical assessment. In a postmortem study with 30 cases whose autopsy findings indicated gross or microscopic injuries to the spinal column or cord, Makino et al. [16] found that six patients (SCIWORA group) had no postmortem multidetector CT (MDCT) scan findings suggestive of direct or indirect trauma to the cervical spine. Although 58% (14/24) of non-SCIWORA cases had MDCT-detectable perivertebral hemorrhage, none of the SCIWORA subjects had hemorrhages detectable in postmortem MDCT images (Figure 2). The results of this study point out that even using a more advanced CT imaging technique such as MDCT may not provide conclusive evidence of spinal cord injury in SCIWORA patients [16].

4.3. Dynamic Imaging. If standard AP and LAT plain X-ray and CT images do not reveal any fracture or dislocation, the stability of the spine can be assessed by dynamic flexion and extension radiographs. Although conceptually dynamic imaging might be seen as an alternative modality in the



(a) (b)

Figure 2: Autopsy photographs of a 44-year-old man found dead near his bicycle. Cause of dead was not explainable based on external examination and investigation. MDCT scan did not reveal any fractures, dislocations, or other signs of trauma. (a) Autopsy revealed perivertebral hemorrhage (arrows) anterior to C6 and C7. (b) Macroscopic axial autopsy photographs show hemorrhage (arrow) in cervical spinal cord at C5. *(Source: with permission from [16].)*

diagnostic algorithm of SCIWORA patients, current evidence does not provide enough support for its routine use. Pang and Pollack [2] obtained dynamic cervical films during the first week after injury in 55 children with SCIWORA and noted that, in most, severe paraspinous muscle spasm prevented adequate flexion. The authors repeated the dynamic films after spasm had subsided and showed late stability in only one patient who had anterior subluxation of C4 on C5 that was masked on previous studies due to spasm [2].

Several investigators have studied the role of dynamic imaging in spinal clearance of obtunded trauma patients and their findings revealed that flexion and extension views do not provide any advantage over CT and are not cost effective as a diagnostic modality in cervical spine clearance [24–26]. Considering that the patients in these studies were unconscious and in a relatively relaxed state [24–26], performing adequate dynamic imaging with meaningful results in conscious SCIWORA patients with paraspinous muscle spasm would be highly unlikely. Hence, we do not recommend using dynamic imaging in SCIWORA patients who already had negative plain X-rays and CT images.

4.4. MRI. The advent of MRI provided superior visualization of the soft tissue structures and enabled better recognition of the pathologies involving intervertebral disks, ligaments, and neural tissues including the spinal cord and nerve roots. As a result, MRI has become the gold standard diagnostic imaging modality in patients with presumed SCI [27]. There are characteristic pathomorphological soft tissue changes in SCIWORA patients that could only be detected using MRI but not in plain films or CT images including spinal cord hematomas, transections, discoligamentous injuries, spinal cord edema, and compression [28–31].

Machino et al. [32] studied MRI examinations from 100 SCIWORA patients. The authors detected changes in signal intensity that could be due to spinal cord hemorrhage, contusion, or edema in 92% of the patients. Furthermore, the authors measured the range of signal changes based on the height of the C3 vertebral body from the patients' own sagittal MRI images and found that larger signal changes were predictive of more severe symptoms and poorer outcomes. Boese and Lechler [33] suggested grouping SCIWORA patients based on MRI findings. Patients with no detectable abnormalities in MRI were defined as Type I, and all the patients with detectable MRI abnormalities were included in Type II. The Type II patients were further divided into three groups: extraneural, intraneural, and coexistence of both intra- and extraneural abnormalities. The latter authors identified 36 studies, including 605 adult SCIWORA patients with reported MRI findings [33]. In 43 patients (7.1%), no MRI abnormalities were detected (Type I), while 562 (92.9%) had abnormal MRI scan results (Type II). Of these, 71 patients (11.7%) had extraneural; 223 patients (36.9%) had intraneural; and 268 patients (44.3%) had combined extra- and intraneural MRI abnormalities. Intraneural abnormalities included edema, hemorrhage, contusion, and partial or complete transection. Extraneural findings were disc herniation, ligamentum flavum bulging, prevertebral soft tissue swelling, or ligamentous abnormalities [33]. There is evidence in the literature suggesting that SCIWORA patients with no detectable MRI abnormalities usually have a better prognosis and recovery rate than the patients with MRI abnormalities [34, 35].

In some cases, repeating the MRI scan may reveal abnormalities which were not evident in the initial examination, or changes in the extent of the previously identified MRI abnormalities [23, 28, 36]. Liu et al. [28] performed MRI in 59 SCIWORA patients with neurological deficiencies at the cervical or thoracic level. Two patients with neurologic deficits were classified as normal on initial MRI. These

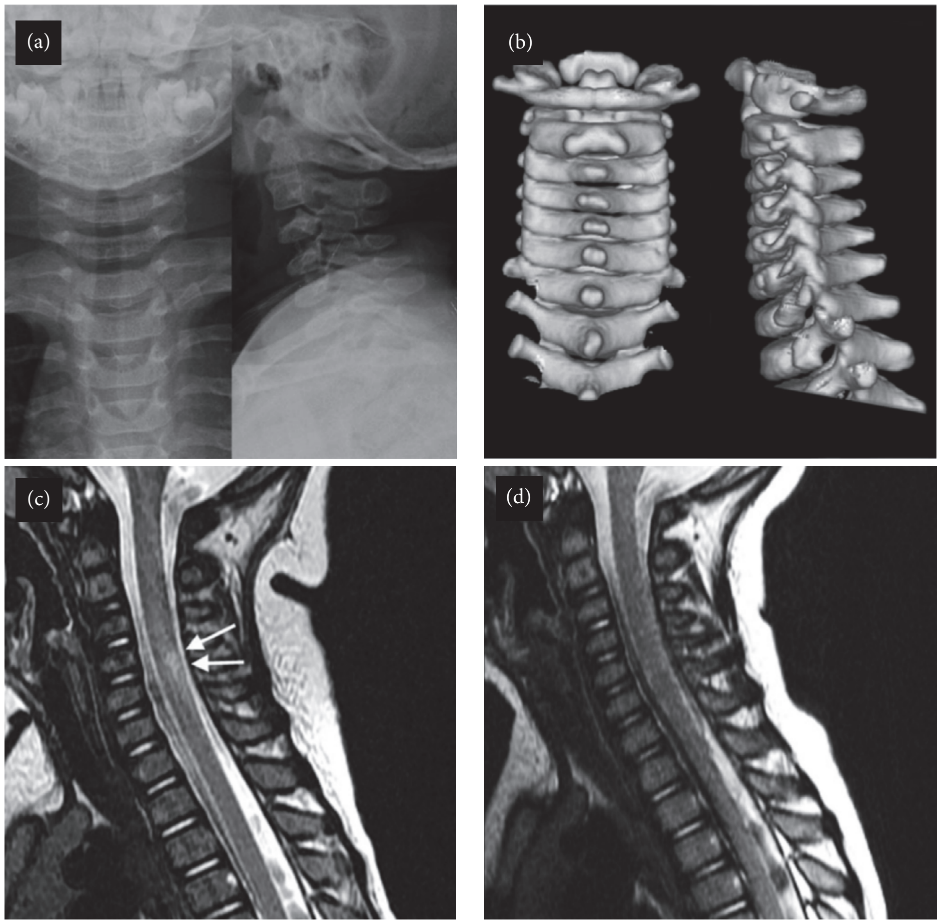


Figure 3: A 12-month-old female infant presented with nausea, vomiting, and drowsiness to emergency room after falling from a height of less than 30 cm. She had no neurological deficit at presentation, and cervical spine plain radiographs (a) and CT with 3D reconstruction (b) showed no abnormal findings. (c) Seven days after the injury the patient developed right sided hemiparesis and cervical MRI revealed increased intensity (arrows) in the T2-weighted images at the level of C6. (d) Repeat cervical MRI one month later shows that increased signal intensity has disappeared. The patient continued to improve neurologically until 24 months after the injury and returned to near-normal. *(Source: with permission from [17].)*

patients had repeat MRI scans 72 hours after the initial trauma, which revealed positive MRI abnormalities, and they underwent surgical interventions. Schellenberg et al. [23] reported on an 18-year-old male who was involved in a car accident as the seat-belted driver. Although the patient presented with paraplegia, his initial plain X-rays, CT, and MRI of the spine were normal. A repeat MRI scan five days after the collision revealed a new abnormal signal (10 mm in size) at the level of T3-T4, representing spinal cord edema. Ouchida et al. [36] performed MRI scan of 68 SCIWORA patients within 48 hours after the injury and repeated the MRIs two weeks after the injury to measure the changes in signal intensity and range. Repeat MRI scans revealed higher-grade signal intensity in 24 patients and attenuation in range of signal intensity as measured based on C3 vertebral height. Moreover, there was a significant negative correlation between the signal intensity grade and range and clinical symptom severity at two weeks. This negative correlation was absent in the acute MRI. The authors suggested that "delayed MRI can provide useful information about the state of the spinal cord after the acute phase..." [36].

Regardless of the timing or number of scans, MRI appears as the sole diagnostic modality that may aid orthopaedic surgeons in understanding the mystery of SCIWORA syndrome, which does not reveal any findings in plain X-rays and CT (Figure 3).

4.5. Somato Sensory Evoked Potentials (SSEPs). SSEPs are signals generated by the nervous system in response to electrical stimulation of a peripheral nerve. Since the SSEP signals are series of waves that reflect sequential activation of neural structures along the somatosensory pathways, monitoring these signals by electrodes positioned along these pathways can aid in detecting any dysfunction from the level of the peripheral nerve, through the spinal root, spinal cord, brain stem, and thalamocortical projections, up to the primary somatosensory cortex. Moreover, recording signal changes both at the craniovertebral junction and at the cortex can help distinguish between a spinal cord injury and thalamic or cortical dysfunction. Although SSEPs are routinely used for intraoperative neuromonitoring during surgery of the spine, literature support for their use in patients with SCIWORA is quite limited [5, 37, 38]. Moreover, evidence shows that SSEP changes are highly specific but not equally sensitive indicators of postoperative/postinjury neurological deficits [39]. Pang [5] used SSEPs as an adjunct in the initial evaluation of children with presumed SCIWORA. In the study of 95 children with SCIWORA, 50 had both MRI and SSEP data. SSEP recordings obtained within 24 hours after injury were found to be slightly more sensitive than MRI in patients with persistent (88% versus 64%, resp.) or transient (39% versus 27%, resp.) neurological deficits. The author suggested "Normal SSEPs should not be counted against an abnormal neurological examination in deciding whether myelopathy is present. Thus, SSEP recording should be regarded as a special rather than a routine test within the diagnostic algorithm of SCIWORA."

5. Treatment

Although Advanced Trauma Life Support (ATLS) protocols and the initial steps of resuscitation after traumatic SCI are universally accepted, the method utilized to approach patients diagnosed with SCIWORA may vary between institutions; no definitive treatment protocol has been established yet.

5.1. Nonsurgical Treatment. Since overt signs of spinal trauma, such as fractures and dislocations, are absent in SCIWORA, nonsurgical strategies, including immobilization and corticosteroid therapy, are the mainstay of treatment. Immobilization immediately after the injury and at the early stages is performed using hard collars for cervical SCIWORA, or restriction of patients' movements with bedrest and log-rolling for thoracolumbar SCIWORA [5]. After the general condition of the patient has improved and other systemic injuries have been addressed, based on the level of SCI, a cervical or cervical-thoracic brace or thoracolumbar orthosis is applied, and the patient is allowed to get out of the bed and walk. Braces or orthosis are used for a minimum of three months until the reassessment of the neurological condition. At three-month follow-up, a decision as to whether the patient should have another MRI is made on an individual basis. Although the latter is the most widely accepted immobilization protocol, some authors suggest using halter traction with a minimal weight for the first three weeks and immobilization in an extended cervical collar until three months after the injury [35]. Interestingly, Bosch et al. [40] reported 21 patients with recurrent SCIWORA; 14 of them sustained their repeat episode while still wearing a rigid type of cervical brace. The remaining seven patients had their second injury either in a soft brace or beyond the time of immobilization. The authors suggested, "Bracing and immobilization do not prevent recurrent SCIWORA or improve outcomes in minor or severe SCIWORA once instability had been properly ruled out." They also stated that "...bracing is not uniformly indicated."

It is imperative to note that evidence to date does not include any randomized controlled trials to prove the superiority of one practice or suggestion over another. However, immobilization of the spine until the spine tenderness clears, the neurologic examination has normalized, and MRI is negative for instability is the universally accepted initial nonsurgical treatment approach [5, 10, 21, 35, 36, 40]. Regardless of the immobilization type, all SCIWORA patients are advised to refrain from any physical activities that may increase the risk of reinjury for approximately six months [21].

Posttraumatic spinal cord damage results from both primary (impact of trauma itself) and secondary mechanisms (subsequent cellular events and inflammatory response) that start at the moment of the injury and go on for days and even weeks [18]. The rationale for the use of steroid therapy in patients with SCIWORA is to prevent or minimize the secondary mechanisms that may cause damage to spinal cord after a traumatic injury. Although there is not enough evidence supporting routine use of high-dose intravenous (IV) methylprednisolone in SCIWORA patients, some studies suggest potential efficacy after SCI if it is started within the first eight hours of trauma with additional benefit by extending the maintenance dose from 24 to 48 hours [41]. Hence, IV methylprednisolone bolus of 30 mg/kg within eight hours of injury, followed by infusion at 5.4 mg/kg/hr for the next 48 hours can be beneficial in improving outcomes. In most SCIWORA cases, IV steroid therapy is started before an MRI scan can be completed and any detailed information with regard to pathological findings is available. Martinez-Perez et al. [8] reported that none of their 48 SCIWORA patients received corticosteroids during their hospitalization. In a prospective study including 45 consecutive SCIWORA patients, Mohanty et al. [35] routinely gave IV methylprednisolone to all the patients for 48 hours. Sharma et al. [9] administered methylprednisolone to seven of their 12 SCIWORA patients and stated "...the number of patients is too small to comment on the efficacy." The effect of high-dose IV methylprednisolone therapy on clinical outcomes in SCIWORA patients requires further investigation.

5.2. Surgical Treatment. There is controversy in the literature regarding surgical treatment of patients diagnosed with SCIWORA. Although the majority of published reports suggest significant improvement in neurological status without operative treatment [17, 28, 31, 35], surgical intervention can become necessary in selected cases if there are clear signs of instability with ligamentous injury and/or cord compression which does not improve [8, 9, 36]. In a series that included 48 adult SCIWORA patients, Martinez-Perez et al. [8] treated 14 patients operatively. Of those 14 patients, six were treated by an anterior approach, and eight underwent decompressive laminoplasty or laminectomy. There was an improvement of at least one point on the ASIA Impairment Scale in 86% of the patients who received operative treatment compared with 76% of the patients who were treated conservatively. In a systematic review, Carroll et al. [10] identified 433 pediatric SCIWORA patients, and there were records of treatment in

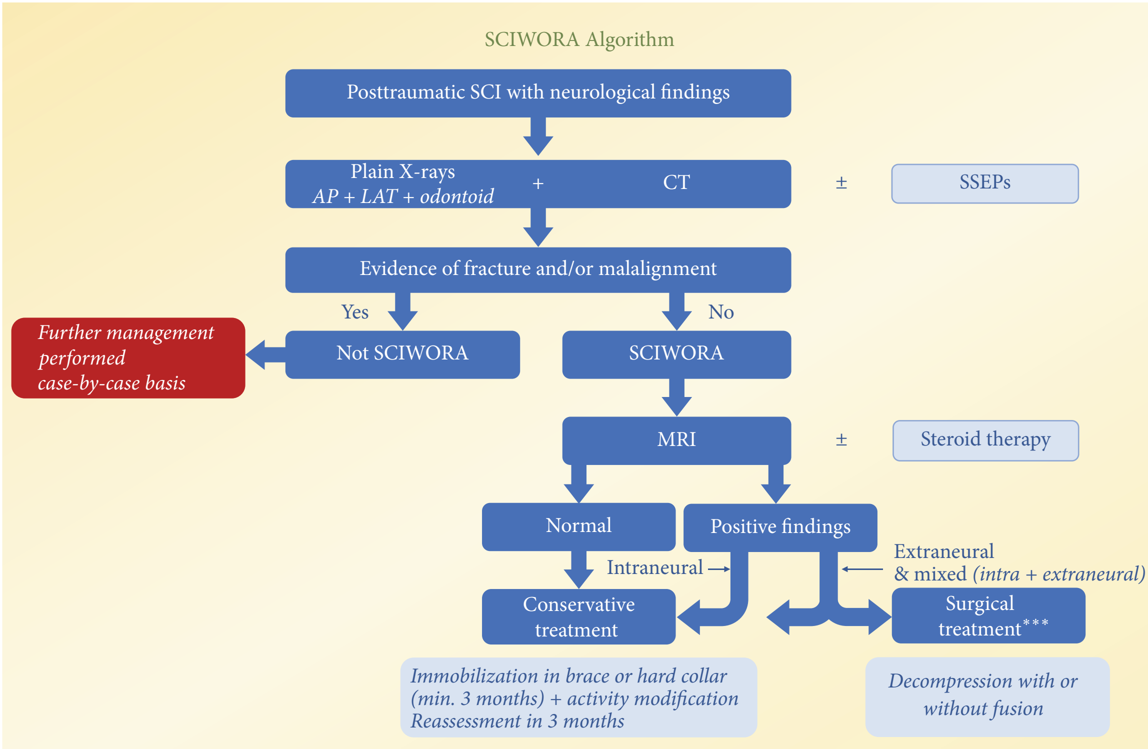


Figure 4: SCIWORA Algorithm. Pure intraneural MRI findings including edema or hemorrhage within the cord parenchyma is not an indication for surgery. Pure extraneural injury including severely injured ligaments or compression even without findings within the cord may be an indication for surgery. Patients with mixed extraintraneural MRI findings have the highest chance to require surgical treatment. Please note that there could be variations in diagnostic work up and treatment based on institutional or surgeons' preferences. ***Main indications for surgical treatment are cord compression and ligamentous instability along with worsening or not-improving neurological findings. *(Courtesy of University of Alabama at Birmingham, Department of Orthopaedic Surgery, Birmingham, AL, USA.)*

183 cases. Of those, only six were treated operatively without notable details in terms of operative indications, technique, or outcomes.

Based on current evidence and our previous experience, surgical treatment is not recommended in SCIWORA patients with normal or pure intraneural MRI findings (i.e., cord edema or contusion without compression) regardless of patient's neurological status. Although clear MRI evidence of ligamentous injury, instability, spinal cord compression along with worsening, or not-improving neurological findings should be indications for surgical decompression with or without fusion, no controlled study to date has compared the outcomes of surgical treatment in SCIWORA patients with outcomes of nonsurgical treatment (Figure 4).

6. Prognosis

In general, most SCIWORA patients show remarkable improvement in neurological status after the injury, and surgical treatment is rarely justifiable. However, the main reason for the priority of conservative treatment in the management of SCIWORA patients is not the mild nature of the injury, but the absence of bony involvement and malalignment. Hence, the injury itself should be recognized as dreadful, and the prognosis can be dismal with devastating complications such as permanent neurological impairments and death [2, 16].

The two main predictors of prognosis after SCIWORA are the initial neurological status and MRI findings [2, 5, 32, 34]. Pang [5] suggests that neurological status at admission is the only predictor of long-term outcome in children with SCIWORA. Children with complete SCI rarely improve. Those with severe but incomplete SCI often improve but seldom regain normal function. In Pang's experience and based on several other reports, patients with mild to moderate initial neurological deficits may have more chance to attain full recovery [5, 8, 28].

Martinez-Perez et al. [8] reported that, at one-year postinjury follow-up, complete recovery in neurological status (AIS grade E) was achieved only in patients with incomplete neurological injury (AIS grades C and D) at admission. Although this study could not demonstrate a significant association between the neurologic impairment at admission with recovery, their results indicate a tendency for the less-severe SCIs to recover completely, while the patients with complete SCIs failed to show any progress. The lack of statistical significance can be explained by limited patient numbers and unequal distribution of the patients to groups with different AIS grades due to retrospective nature of the study.

Correlation between the MRI findings and prognosis has been the focus of several investigators [9, 28, 32, 34–36]. Mohanty et al. [35] showed significant negative correlations ($P < 0.05$) between the length of MRI changes in the spinal cord and the recovery rate (−0.026) as well as the final motor score (−0.042). There was a significant negative correlation between the length of prevertebral hyperintensity in MRI and AIS at the time of presentation ($P < 0.001$), final follow-up ($P < 0.001$), and the rate of recovery ($P < 0.001$). Authors reported that SCIWORA cases with normal MRI findings and spinal cord edema showed a higher mean recovery rate at two years after the injury (95.56 ± 12.54 and 87.70 ± 21.67, resp.). The rates of recovery in patients with MRI findings of cord contusion and cord swelling were the lowest among the groups (48.72 ± 42.08 and 39.42 ± 1.68, resp.), and the differences in recovery rates between different spinal cord changes were statistically significant ($P < 0.05$). Supporting these results, Boese et al. [34] showed that the mean improvement of AIS grade in SCIWORA patients with no MRI abnormalities was higher compared to those with detectable MRI abnormalities (1.5 versus 0.9, resp.). These authors also noted that all the patients who required surgical decompression were presented with simultaneous extra- and intraneural MRI findings.

Although long-term prognosis (over two years) of SCIWORA patients has not been studied extensively in large patient groups, expecting further improvement in neurological status after the first two years may not be realistic. However, worsening in the long-term due to recurrent injuries and/or development of deformities has been reported by several authors [40, 42]. Bosch et al. [40] had 21 patients with recurrent SCIWORA; of those, 20 were older than eight years of age at the time of initial injury. Furthermore, recurrences occurred up to three years after the initial event. The majority of recurrences happened during sports activities, and this may explain the higher recurrence rate among children over eight years of age. Yalcin et al. [42] reported four patients who developed progressive neuromuscular scoliosis due to SCIWORA. Spinal deformities were first noticed at a mean of 17 months after the initial injury that led to surgical interventions at a mean of 6.5 years.

7. Summary

SCIWORA is a syndrome that defines posttraumatic SCI in patients with neurological findings without any evidence of fractures or malalignment in plain X-rays and CT. This condition is more commonly seen in the pediatric age group, with a predilection for the cervical spine. Proposed mechanisms of injury include hyperflexion, hyperextension, and parenchymal cord damage resulting from edema or vascular injury that can occur as a result of sports injuries, falls, and motor vehicle collisions. Diagnostic evaluation starts with a detailed history and physical examination, followed by plain X-rays and CT. SSEPs can be done selectively; dynamic imaging does not provide any additional information and has been dropped from the diagnostic algorithm in SCIWORA. With its superior ability to reveal soft tissue pathologies and prognostic value, MRI is accepted as the imaging modality of choice in patients diagnosed with SCIWORA. Nonsurgical treatment with cervical brace or collar for a minimum of three months and restriction of high-risk activities for six months is the mainstay of treatment. Steroid therapy has not proven to be effective in SCIWORA patients. Based on evidence from studies in patients with SCI in general, it can improve the outcomes if started within eight hours of injury and continued for 48 hours. Surgical treatment should be reserved for patients with clear MRI evidence of extraneural findings including spinal cord compression, ligamentous injury, and instability, along with worsening or not-improving neurological findings. Prognosis of SCIWORA depends on the initial neurological deficit and extent of spinal cord injury as evidenced by MRI. Although neurological improvement in patients with complete neurological deficit at initial presentation is highly unlikely, most patients with incomplete neurological injury show improvement. Even so, permanent disabilities and deformities in the long-term are among the complications encountered by SCIWORA patients.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Epidemiology of C2 Fractures in the 21st Century: A National Registry Cohort Study of 6,370 Patients from 1997 to 2014

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Objective. C2 fractures are a common injury in the elderly population. Treatment is often complicated due to osteoporosis and patient comorbidity. This study aims to investigate the incidence and treatment trend of C2 fractures in Sweden. *Methods*. Patients with the principal and secondary diagnosis of fracture of the second vertebrae (ICD-10: S12.1) between 1997 and 2014 were identified in the Swedish National Patient Registry (NPR). *Results*. Between 1997 and 2014, 6,370 patients with a C2 fracture (51% male; age: 72 ± 18) were identified in the NPR. The incidence of C2 fractures increased from 3 to 6 per 100,000 ($r = 0.94$; $p < 0.01$), mainly due to an increase of incidence in the geriatric subgroup (≥70 years). The percentage of surgically treated patients decreased from 1997 to 2014 ($r = -0.80$; $p < 0.01$). Younger age, male gender, spinal cord injury, and earlier year of admission were associated with surgical treatment assignment. *Discussion*. This study documents a rising incidence of C2 fractures in the elderly during the last two decades in Sweden. Greater awareness of fractures, improved diagnostics, coding, and a higher activity level of the patients are plausible causes. The declining trend of surgical treatment warrants further study.

1. Introduction

Fractures of the second cervical vertebra (C2) are a common injury in both the elderly and the young and active population [1]. Previously published studies find 9–18% of cervical fractures to be C2 fractures, of which 35–78% are odontoid process fractures and 11–25% are traumatic C2 spondylolysis, Hangman's fractures [2–6].

In the elderly, the proportion of C2 fractures is greater than that in the younger population [7, 8]. The elderly population has grown during the last decades [9]; therefore it is likely that the incidence of C2 fractures has increased as well. About 89% of the C2 fractures in patients ≥ 70 years of age in two tertiary referral centres in Sweden are odontoid fractures [8]. On a regional level in Sweden, we report a growing incidence of elderly patients with C2 fractures, which has not been seen in the younger population [8].

Surgical treatment options vary depending on the type of C2 fracture. Odontoid fractures type 2 are commonly treated with anterior screw osteosynthesis or posterior C1-C2 fusion [10–13]. Hangman's fractures are treated surgically with anterior C2-C3 fusion, posterior direct osteosynthesis, or posterior C2-C3 fusion [14, 15].

Nonsurgical treatment of C2 fractures is commonly performed with a rigid cervical collar [16]. In cases of instability or dislocations a halo-vest treatment is possible [17, 18].

The availability of prospectively collected data in nationwide registries in Sweden allows tracking of epidemiology retrospectively without the necessity of repeated cross-sectional trials. This study aims to investigate the incidence and treatment trend of C2 fractures during the last two decades in the Swedish National Patient Registry.

2. Patients and Methods

2.1. Study Design. This national multiregistry cohort study used prospectively collected electronic healthcare data from the Swedish National Patient Registry (NPR) and Statistics Sweden between 1997 and 2014. The study protocol was approved by the Institutional Ethical Review Board (2010/131/1) and follows STROBE and RECORD statements [19].

2.2. Setting. The Swedish National Patient Registry is hosted by the Swedish National Board of Health and Welfare and contains all patient contacts within Sweden with a coverage of >90% for orthopaedic diagnoses [20]. Registered are main diagnosis and comorbidity using the International Classification of Diseases, Ninth Revision (ICD-9), until December 1996 and since then the ICD-10 code [21]. In the International Classification of Diseases, Tenth Revision (ICD-10), there is no subclassification for C2 fractures [21]. Treatment has been coded since 1997 using the Swedish classification of surgical procedures [22]. Furthermore, information on hospitalisation time is available from the registry. Statistics Sweden is an administrative agency, providing statistics to the government, different agencies, and researchers.

2.3. Participants. All patients registered with the main and secondary diagnosis of C2 fracture treated between 1 January 1997 and 31 December 2014 were extracted from the NPR. In this study, we wanted to calculate the incidence and treatment trend, and therefore both main and secondary diagnoses were included, so that most possible C2 fractures would be included for calculations. Prior to data transmission, the Swedish National Board of Health and Welfare anonymised the individual personal identification numbers using a key that remained with the agency. Patients younger than 20 years of age and older than 99 years at the date of fracture were excluded. Population registry data from January 1997 until December 2014 were abstracted from Statistics Sweden. An inclusion flow diagram was prepared according to CONSORT statements [23].

2.4. Variables. The ICD-10 code S12.1 (fracture of the second vertebrae) was used to identify patients with C2 fracture in the NPR. ICD-10 has been validated for all diagnosis with an accuracy from 89 to 95% [20] and also for orthopaedic diagnosis with an accuracy of 95% for principal and secondary diagnoses until the third position and 90% to the fourth position [24]. The specificity of the ICD-10 code S12.1 has been validated in a dataset of 172 patients with ICD-10 S12.1 from 2002 to 2014, where 0% false positive cases were found (specificity = 100%). Baseline data for the included individuals were collected from the NPR and presented in tabular form. Causes of injury codes were not extracted from the NPR, due to, for our purposes, unacceptably low accuracy of these codes [20, 24]. Patients receiving surgical treatment were identified, using Swedish surgical procedure codes for spinal fusion (“NAG”) and spinal fracture treatment (“NAJ”). Nonsurgically treated cases with a change of treatment modality to surgery were registered as surgical patients. Subgroup analysis was performed for nongeriatric (20–69 years) and geriatric patients (70–99 years) and for nonsurgical and surgical treatment.

2.5. Statistical Methods. All statistical calculations were programmed in R version 3.3.0 (R Foundation for Statistical Computing, Vienna, Austria) [25]. Mean values were presented ± standard deviation if not indicated otherwise. Groups were compared with t-test for normally distributed variables; otherwise the Wilcoxon test was applied. Trends were analysed with linear regression and presented with correlation coefficient r. Group proportions were tested with χ^2 test. $p < 0.05$ was regarded as statistically significant. The age distribution differences of patients with C2 fractures treated with and without surgery were visualised with a density distribution plot. A logistic regression analysis identified covariates of surgical treatment assignment and was presented with 95% confidence intervals (CI) and statistical probability p [26]. As relevant covariates in a model for surgical treatment assignment, age [27], gender [28], CCI [29], and SCI [30] were determined by literature review. Before removing the cases below 20 years of age and older 100 from the dataset, a histogram of the age-related frequency of C2 fractures was prepared.

2.6. Data Access and Cleaning Methods. The authors did not have direct access to the national registry databases in this study but were provided with a predefined extract from the national registries by the Swedish National Board of Health and Welfare (specification number: 13062/2015).

Even though a clean patient registry dataset was provided, duplicates (recurrent admissions of the same patient or continued treatment in a secondary facility) had to be identified and removed from the extract. The secondary diagnoses of the duplicates were added to the original record prior to duplicate exclusion.

3. Results

3.1. Participants. The population of 20 to 99 years of age in Sweden 1997 was 6,689,671 (mean age: 39.9 years), and in 2014 it was 7,536,133 inhabitants (mean age: 41.2 years). Between 1997 and 2014, a total number of 11,077 cases were treated as inpatients due to a C2 fracture. The inclusion flow chart is shown in Figure 1.

3.2. Descriptive Data. 6,370 patients with the principal and secondary diagnosis of a C2 fracture (ICD-10: S12.1) were included. 51% were male. The mean age was 72 ± 18 years. The group was divided into nongeriatric patients < 70 years of age ($n = 2{,}256$) and geriatric patients ≥ 70 years of age ($n = 4{,}114$). 26% received surgical treatment: 34% in the nongeriatric group and 22% in the geriatric group (χ^2 test, $p < 0.01$). Stratified for gender (51% male, 49% female), 31% male and 22% female patients received surgical treatment (χ^2, $p < 0.01$).

Baseline data is shown in Table 1. The Charlson Comorbidity Index (CCI) was 4.9 ± 2.5, and spinal cord injury (SCI) was present in 2% ($n = 140$). 10% ($n = 630$) had a concomitant C1 fracture.

3.3. Outcome Data

3.3.1. Incidence of C2 Fractures. The incidence of C2 fractures doubled from 1997 to 2014 from 3 to 6 per 100,000 inhabitants

Table 1: Baseline values of patients according to treatment presented as count (n) or mean ± standard deviation.

	n	Age	Sex		CCI	SCI	C1	Spinal fracture			Surgical technique	
			Male	Female				Subaxial	T	L	Screw	Fusion
		Years	n	n		n	n	n	n	n	n	n
Surgical	1681	68 ± 17	1013	668	4.4 ± 2.3	77	236	194	90	30	168	1513
Nonsurgical	4689	73 ± 18	2277	2412	5.1 ± 2.6	63	394	272	186	122	0	0
All	6370	72 ± 18	3290	3080	4.9 ± 2.5	140	630	466	276	152	168	1513

n: number; SD: standard deviation; CCI: Charlson Comorbidity Index; SCI: spinal cord injury; T: thoracic; L: lumbar.

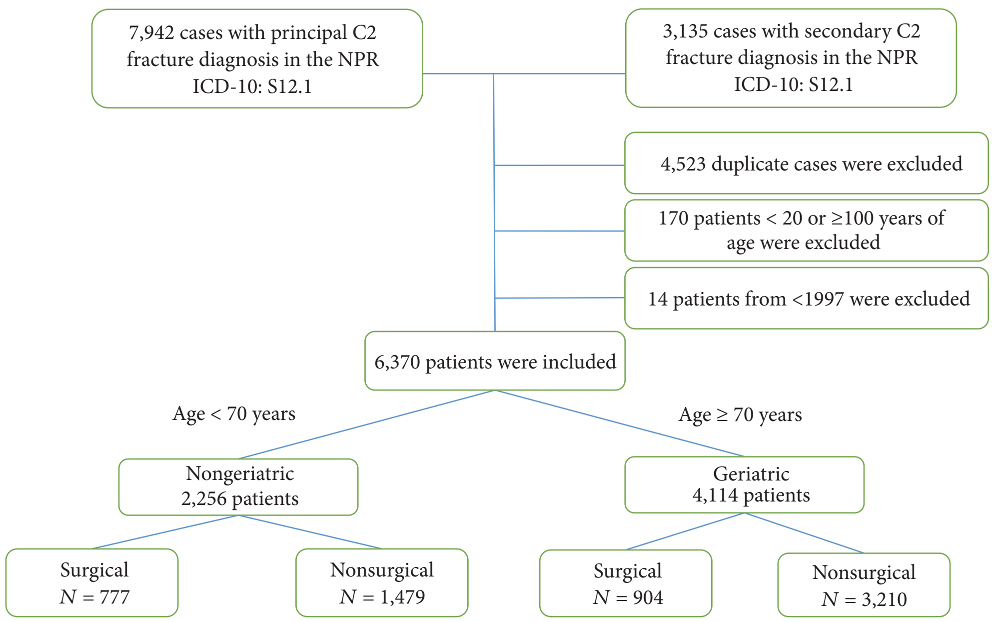

Figure 1: Inclusion flow diagram.

($r = 0.94$; $p < 0.01$). The incidence in the geriatric group increased linearly from 10.2 to 23.7 per 100,000 from 1997 to 2014, which was not found in the nongeriatric group (Figure 2) ($r = 0.89$; $p < 0.01$).

There was no significant difference of the C2 fracture incidence between the sexes in the subgroup of 80–89 and 90–99 years of age ($p = 0.43$ and $p = 0.46$). With regard to patients below the age of 80 years, C2 fractures were more common in men ($p < 0.01$) (Table 2). A bimodal distribution of age-related C2 fracture frequency was found with peaks at 20–25 years and at 80–85 years (Figure 3). From 1997 to 2014, the C2 fracture incidence quadrupled in the old geriatric patients (90–99 years), while it more than doubled in the age group of 80–89 years and it increased by 30% in the age group of 70–79 years (Figure 4).

3.3.2. C2 Fracture Treatment Trends in Sweden. Of the included patients, 26% were treated surgically. There was a higher density of nonsurgical treatment in the elderly (Figure 5). There has been linear trend from 1997 to 2014 towards nonsurgical treatment ($r = -0.8$; $p < 0.01$) (Figure 6). There was an even stronger trend towards nonsurgical treatment in the geriatric subgroup ($r = -0.95$; $p < 0.01$), compared to the younger age group. Treatment trends are shown in Figures 5, 6, and 7.

In a logistic regression model, the odds ratio of surgical treatment assignment was significantly greater for younger age, male gender, SCI, and earlier year of admission (Table 3).

4. Discussion

4.1. Key Results. This study documents a growing incidence and a declining surgical treatment trend of C2 fractures in the elderly during the last two decades in Sweden.

4.2. Interpretation

4.2.1. Incidence of C2 Fractures. Since 1997, the incidence of C2 fractures has risen from 3 to 6 per 100,000. As the elderly population has grown dramatically in Sweden, the number of hospital admissions due to elderly-specific C2 fractures increased during the last decade. Despite the 64% increase in the population of 90 to 99 years of age from 1997 to 2014,

Table 2: Incidence of C2 fractures per 100,000 within age subgroups according to gender (presented with p values of t-test for gender difference).

Age category Years	Female Per 100,000	Male Per 100,000	Both sexes Per 100,000	t-test p value
20–29	0.8	2.1	1.5	<0.01
30–39	0.5	1.4	1.0	<0.01
40–49	0.8	2.1	1.4	<0.01
50–59	1.7	3.0	2.4	<0.01
60–69	3.9	5.9	4.9	<0.01
70–79	9.2	13.6	11.2	<0.01
80–89	26.2	28.8	27.2	0.43
90–99	49.7	55.2	51.1	0.46

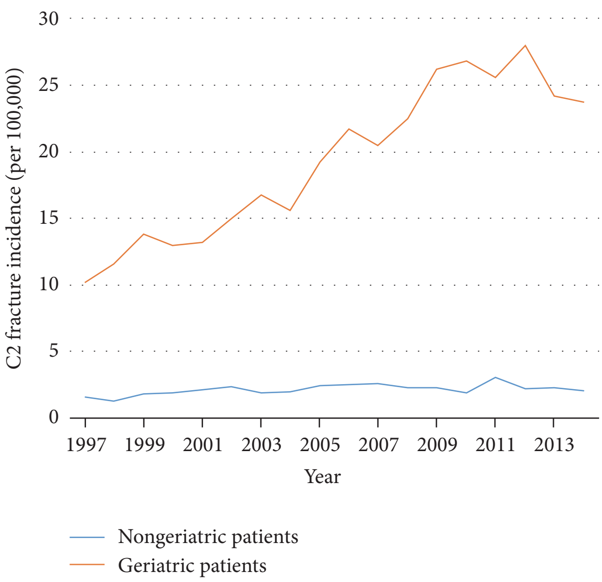

Figure 2: C2 fracture incidence per 100,000 of nongeriatric (blue) and geriatric (red) patients between 1997 and 2014.

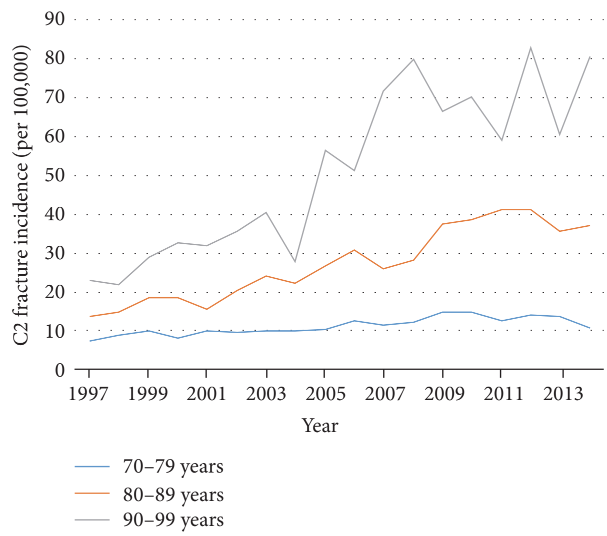

Figure 4: Incidence of C2 fractures between 1997 and 2014 per 100,000 in geriatric age categories: 70–79 years (blue), 80–89 years (orange), and 90–99 years (grey).

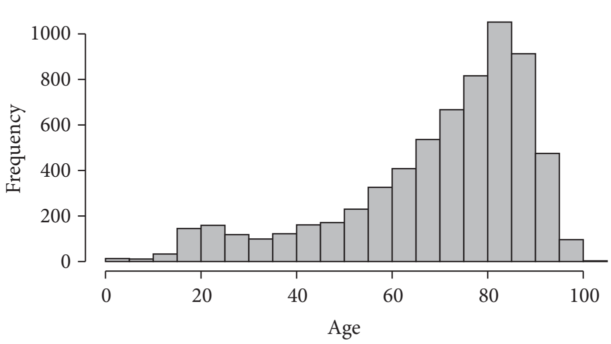

Figure 3: Age distribution of C2 fractures.

a 4-fold increase of the population-adjusted incidence of C2 fractures was found. This compares to the 70–79 years of age population which only increased by 13% but C2 fractures increased by 43%.

One explanation for the increased incidence of C2 fractures is a diagnostic bias, as we nowadays use a computed tomography instead of conventional radiographs as a first diagnostic instrument [31]. Beyond that, the number of falls in the elderly is substantial [32]. There is an increased rate of falls, 78%, for those with four or more risk factors [33, 34]. 5% of the falls cause a fracture [34]. The elderly receive better treatment for comorbidities compared to decades ago [35]. This leads to a higher activity level of the elderly, along with a higher risk of falling, but also the inactive persons stand a high risk of falls [32]. The orthostatic effect of medication like benzodiazepines and antihypertensive drugs may also lead to falls. Furthermore, the fact that the healthcare system in Sweden encourages geriatric patients to live in their own homes instead of nursing homes affects possibilities of supervision and accessibility, a plausible cause of domestic falls [35, 36]. Otherwise, patients at nursing homes stand a higher risk of falls [32, 34]. The combination of falls, a

Table 3: The assignment to surgical treatment was dependent on younger age, male gender, spinal cord injury, and earlier year of admission. Odds ratios are presented with 95% CI and p value.

	OR	95% CI 2.5%	95% CI 97.5%	p
Age	0.99	0.99	1.00	0.012
Male gender	1.42	1.26	1.59	<0.001
Spinal cord injury	2.94	2.08	4.16	<0.001
Charlson Comorbidity Index	0.96	0.92	1.00	0.072
Year of admission	0.96	0.94	0.97	<0.001

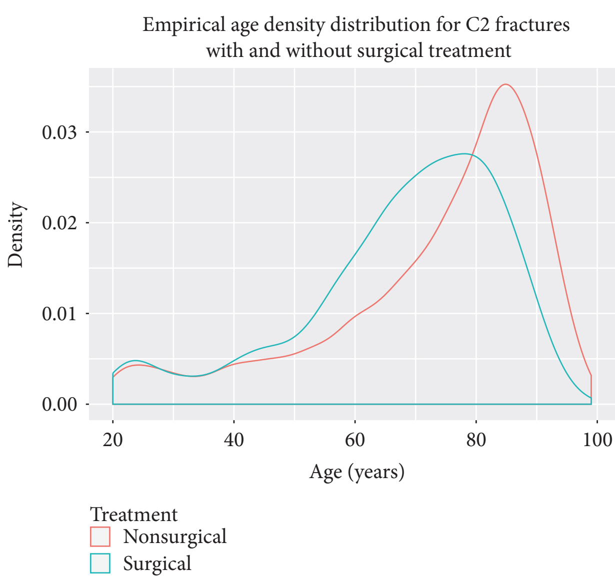

Figure 5: Empirical age distribution for C2 fractures with and without surgical treatment.

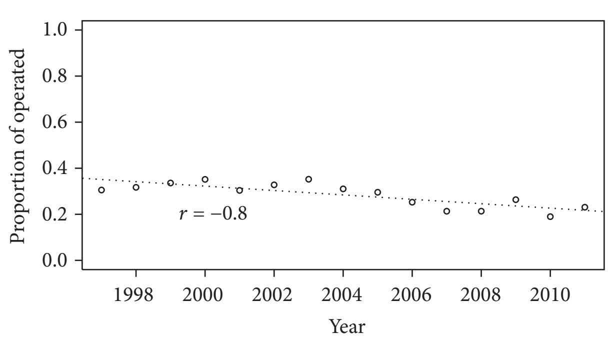

Figure 6: Annual proportion of surgically treated patients with C2 fractures.

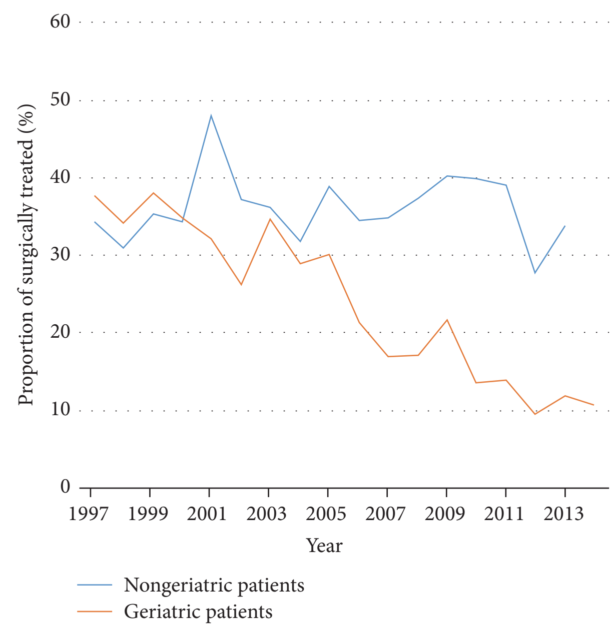

Figure 7: Proportion of surgically treated nongeriatric (blue) and geriatric (orange) patients with C2 fractures between 1997 and 2014.

stiff lower cervical spine, and osteoporosis could explain the increased incidence of C2 fractures in the elderly [37, 38].

4.2.2. C2 Fracture Treatment Trends in Sweden. There was a national trend towards nonsurgical treatment of C2 fractures in Sweden, foremost in the elderly, which does not confirm previously published results from other countries [37, 39, 40]. Fear of overtreatment could be a factor contributing to the trend of nonsurgical treatment of cervical fractures. The elderly patients' comorbidity could explain the physicians' tendency to use a cervical collar in the belief of avoiding harm. In contrast, recently published results suggest that surgical C2 fracture stabilisation reduces morbidity and mortality of elderly patients with greater comorbidity [37, 41]. In this registry study, we could not perform a subgroup analysis of C2 fracture subtypes, level of dislocation, or treatment allocation. Several authors recommend a treatment based on level of fracture dislocation besides comorbidity and age; this could not be investigated in our cohort [2, 6, 42].

4.2.3. Gender Differences in Treatment Assignment. This study pinpointed that men and women were treated differently. The proportion of women treated surgically was much lower than men. Thus, female patients received a probably inferior treatment with regard to survival [43]. Multiple studies have documented an implicit, unintended discrimination of female patients by their physicians [44, 45]. As treating surgeons, we should accept and acknowledge the fact that our treatment decisions are unintentionally affected by stereotypes as gender [40]. This will allow us to minimise implicit gender discrimination.

4.3. Strengths and Limitations. Due to the unmatched coverage and the high internal validity of the Swedish patient registry, the presented data is reliable. The national population-based cohort design of this study minimises the selection bias of tertiary referral centres. These often attract odd and unusual case referrals and distort the disease panorama. This national registry study has therefore advantages over many previously published cohort studies. Furthermore, registry studies have the strength of including the whole population instead of creating a sample of the population (as you would do in randomised controlled trials) [37]. This allows identification of even rare diseases or complications of treatments.

As the ICD-10 does not allow the differentiation of odontoid fractures from other C2 fractures, the NPR could not answer the question of proportion of C2 fracture subtypes. In a previous study from two regions in Sweden, we have revealed that about 63% of the C2 fractures are odontoid type 2 fractures in the elderly population $\geq$ 70 years, and 26% are odontoid type 3 fractures [8]; this means that a total 89% of the odontoid fractures in the elderly are either type 2 or type 3. We described an increase in the proportion of odontoid C2 fractures in the elderly from 2002 to 2014. Therefore, one can assume that the increase of C2 fractures in the geriatric subgroup from 1997 to 2014 found in the present study was largely due to an increase of odontoid type 2 and type 3 fractures. In the younger age group, our previous study from Sweden revealed a more differentiated panorama of C2 fractures, including 24% Hangman's fractures, 21% atypical fractures, 17% odontoid type 3 fractures, and 34% odontoid type 2 fractures [8]. In the present nationwide study, C2 fractures of the nongeriatric patients did not increase (Figure 2); thus, any conclusions regarding the C2 fracture subtype distribution would be speculative.

The availability of computed tomography for diagnostics of cervical injuries in the last two decades could have led to a diagnostic bias, where a greater number of C2 fractures would be detected during the recent years of this study [46, 47].

As the validity of the 4th digit of the fracture ICD-10 code (90%) is lower than the third digit (95%) [24], approximately 5% of C2 fractures were likely to be misdiagnosed as other cervical spine fractures (S12.0, S12.2, S12.7, S12.8, and S12.9). In contrast, the risk that fractures that are not C2 fractures were misdiagnosed as S12.1 is low, since the specificity of S12.1 was 100% (unpublished data).

A confounder not controlled for in this study is the comorbidity of osteoporosis. If the population's osteoporosis improved (i.e., due to better preventive healthcare measures), this would affect the risk of cervical spinal fractures [35].

As most other countries, Sweden has a geographically, health-economically, and ethnically unique population. The results presented in this study might not be generalizable to the rest of the world. Studies from national patient registries in other countries will have to validate our results in their specific settings.

5. Conclusion

This study identified an increased incidence of C2 fractures during the last decade along with a decreased proportion of surgically treated elderly patients. Results from ongoing randomised controlled trials, as the U-SOFT trial (ClinicalTrials.gov # NCT02789774), will facilitate an evidence-based treatment rationale for C2 fractures.

Conflicts of Interest

The authors declare the following possible conflicts of interest regarding the publication of this article: Claes Olerud and Yohan Robinson are board members of the European section of the Cervical Spine Research Society. Yohan Robinson is chairman of the AOSpine Nordic Region. Anna-Lena Robinson, Claes Olerud, and Yohan Robinson gave paid lectures at courses sponsored by DePuy Synthes and Medtronic.

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