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MANAGEMENT OF PELVIC RING INJURIES

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To my Family

ABSTRACT

Pelvic ring disruptions are relatively uncommon; they account for approximately 1% of fractures that require hospitalization in Finland. Unstable pelvic fractures typically result from high-energy traumas, which carry an increased risk of associated injuries to other body regions. Among patients with multiple injuries, up to 25% have a pelvic ring injury. Massive hemorrhage is the leading cause of potentially preventable death following a blunt pelvic trauma. When not treated promptly, hemorrhage leads to cardiovascular collapse and death. Appropriate assessment and treatment of these injuries, and associated injuries in other organs, are essential for achieving better survival rates and reducing long-term disability.

The purpose of this study was to evaluate the usefulness of an anterior trapezoidal external fixator as a definitive treatment for type B and C pelvic ring injuries. This study aimed to evaluate the results of treating pelvic arterial hemorrhage with transcatheter angiographic embolization (TAE) in an emergency facility, and to identify mortality-related prognostic factors for evaluating pelvic fracture-related arterial bleeding. This study also aimed to evaluate the radiological and functional outcomes for type C pelvic fractures treated with standardized techniques for internal fixation of the posterior and anterior parts of the pelvic ring. Additionally, this study aimed to evaluate the radiological and clinical outcomes, including neurologic recovery, after lumbopelvic fixation and neural decompression in H-shaped sacral fractures with spinopelvic dissociation and, to uncover prognostic factors related to outcome. The study populations consisted of various groups of patients with pelvic traumas treated between 1982 and 2011 at our level I trauma centre.

The results showed that an anterior trapezoidal external fixator failed to achieve and properly maintain reduction in three-fourths of type B open book injuries and in nearly all (95%) type C pelvic ring injuries. On the other hand, type B lateral compression injuries are relatively stable, and this injury could be stabilized adequately with an anterior external frame, when indicated, but compression should be avoided during a closed reduction and application of the fixator.

The study showed that, upon admission for exsanguinating bleeding, very low base excess (BE) values (<-10.0 mmol/l) had an increased risk of death. Sequential measurements of BE during the first 12 h after admission provided estimates of the severity of pelvic fracture-related bleeding. The worst prognosis was related to exsanguinating bleeding from the main trunk of the internal or external iliac artery (large pelvic arteries) or from multiple branches of the internal or external iliac vasculature (high vessel size score). Assessment and definitive control of arterial bleeding was achieved with TAE in all patients. Although, rupture of the external iliac artery was rare, it indicated a need for prompt use of surgical techniques to control bleeding and restore blood flow to the lower leg.

Initial resuscitation of patients that were bleeding required prompt provisional stabilization of the pelvic ring and urgent control of arterial bleeding. In a critical situation, with several bleeding arteries uni- or bilaterally, it is reasonable to embolize the main trunk of the internal iliac artery (non-selective embolization) to gain prompt control of bleeding. In exsanguinating bleeding, a damage

control protocol may include temporary extraperitoneal pelvic packing or resuscitative aortic occlusion with a balloon to achieve early hemorrhage control and provide time for a more selective embolization approach to the bleeding. A multidisciplinary approach provided the best chance of survival.

The study of operatively treated type C pelvic fractures revealed that, in this group of patients, internal fixation of all injuries in the posterior and anterior pelvic ring provided excellent or good radiological results in 90% of cases. Additionally, because an anatomical or near anatomical reduction (displacement ≤ 5 mm) was more often associated with a good functional outcome, that should be the goal of operative management. However, the prognosis is also often dependent on associated injuries, particularly a permanent lumbosacral plexus injury. Conversely, it is unusual to obtain a satisfactory result in the presence of a fair or poor fracture reduction. The less invasive posterior approach and the new anterior intrapelvic approach proved to be safe, with low complication rates. The results favoured internal fixation of all the injured elements of the pelvis for improved stability and a more accurate anatomical result in the entire pelvic ring.

The H-shaped sacral fracture with spinopelvic dissociation is a rare injury pattern. This study revealed that lumbopelvic fixation was a reliable treatment method for these injuries, because no reduction failures occurred. However, the Roy-Camille classification of these fractures (1985) was not prognostic of neurological impairment after operative treatment. This study showed that neurological recovery and clinical outcome were associated with the degree of initial translational displacement of the transverse sacral fracture. Permanent neurological deficits were more frequent in patients with complete transverse sacral fracture displacements than in patients with only partially displaced sacral fractures. Also, the clinical outcome was worst in completely displaced transverse sacral fractures. The quality of reduction was assessed in terms of (1) the residual postoperative translational displacement and kyphosis in the transverse sacral fracture and (2) the residual vertical and AP displacements in the vertical sacral fracture lines; these qualities were also associated with the clinical outcome. An accurate reduction of all fracture components was associated with better clinical outcome. It was useful to subcategorize transverse sacral fractures, as partially displaced or completely displaced, for improved predictions of the prognosis for neurological recovery following operative reduction and lumbopelvic fixation. Adding these subcategories to the original Roy-Camille type 2 and 3 sacral fractures would facilitate preoperative planning and estimations of prognosis for patients with H-shaped sacral fractures with spinopelvic dissociation.

TIIVISTELMÄ

Lantiorenkaan murtumat ovat suhteellisen harvinaisia vammoja käsittäen 1% kaikista sairaalahoitoa vaativista murtumista Suomessa. Epätukevat lantiorenkaan murtumat syntyvät yleensä suuren vammaenergian seurauksena ja niihin liittyy usein muiden kehonosien vammoja. Monivammapotilaista jopa neljäsosalla on todettu lantiorenkaan murtuma. Massiivinen verenvuoto on merkittävin ja usein estettävissä oleva kuolinsyy tylpällä vammamekanismilla syntyneissä lantiorenkaan vammoissa. Mikäli akuuttivaiheen hoito ei ole tehokasta, massiivinen verenvuoto johtaa sydämen ja verenkierron pettämiseen ja potilaan kuolemaan. Systemaattisella tutkimisella sekä määrätietoisella ja vaikuttavalla hoidolla voidaan vähentää tähän vammatyyppiin liittyvää kuolleisuutta, sairastavuutta ja pysyvää vammautumista.

Tutkimuksen tarkoituksena oli selvittää ulkoisen tukilaitteen soveltuvuus B- ja C-tyypin lantiorenkaan murtumien lopulliseksi hoitomuodoksi. Tutkimuksessa selvitettiin hengenvaarallisten, runsaasti vuotavien lantionmurtumien alkuvaiheen vuodon tukkimista embolisaation avulla (TAE). Samalla kartoitettiin riskitekijöitä, jotka ennustavat huonoa lopputulosta ja potilaan kuolemaa vaikeimmin vammautuneiden lantionmurtumapotilaiden kohdalla. Tutkimuksessa selvitettiin myös C-tyypin murtumien kohdalla standardoidun leikkaushoidon ja sisäisen kiinnitysmenetelmän luotettavuutta ja hoidon pitkäaikaistulokset. Tutkimuskohteena oli lisäksi selvittää ristiluun vaikeimpien ns. H-tyypin murtumien leikkaushoidon luotettavuutta sekä saavutetun asennonkorjauksen, murtumakiinnityksen ja hermorakenteiden vapautuksen pitkäaikaistulokset sekä toipumisennusteeseen vaikuttavat tekijät.

Tulokset osoittivat, että lantiorenkaan etuosaan kiinnitettävä ulkoinen kiinnityslaite (externi fiksaatiolaite) ei ollut luotettava, eikä sillä voitu taata asianmukaista murtuman paikalleen asettamista 75%:ssa lantiorenkaan avautumisen aiheuttavissa vammoissa (nk. B-tyypin open book vamma), eikä käytännössä lainkaan vaikeimmissa, täysin epätukevissa C-tyypin murtumissa.

Tutkimus osoitti, että vuotavien lantionmurtumien kohdalla alkuvaiheen laboratoriokokeista ainoastaan merkittävä veren emästasapainon häiriö, matala base excess (BE) arvo (<-10.0 mmol/l) oli yhteydessä huonompaan eloonjäämisen ennusteeseen. Alkuvaiheessa toistetut BE-määritykset auttavat arvioimaan lantiovammaan liittyvän verenvuodon vaikeusastetta. Huonoin ennuste liittyi lantiovammoihin, joissa valtimoiden varjoainekuvauksessa (angiografiassa) todettiin lantion päävaltimon (arteria iliaca interna tai externa) repeämä tai useampia samanaikaisia pienempien valtimosuonten repeämiä. Embolisaatio osoittautui luotettavaksi hoitomenetelmäksi ja kaikki valtimoperäiset vuodot pystyttiin tukkimaan. Ainoan poikkeuksen muodosti arteria iliaca externa päärungon vaurio, joka hoidettiin kirurgisesti, jolloin samalla kyettiin palauttamaan verenkierto alaraajaan.

Vuotavan lantionmurtumapotilaan hoito edellytti epätukevan lantiorenkaan väliaikaista tukevoittamista sekä nopeaa ja tehokasta vuodon tyrehdytystä. Kriittisessä vuototilanteessa, jossa angiografiassa todetaan useita vuotokohtia lantion valtimoissa, tulee embolisaatio suorittaa ei-selektiivisesti siten, että lantion aluetta suonittava päävaltimo (arteria iliaca interna) tukitaan välittömästi. Näin vuoto saadaan nopeammin hallintaan ja potilaan selviytymisennuste paranee. Kriittisessä lan-

tiovuodossa voidaan vaihtoehtoisesti käyttää väliaikaista nk. lantion pakkausmenetelmää, jossa leikkauksellisesti lantioon asetetuin leikkausliinoin aikaansaadaan vastapaine estämään vuotoa tai aortan alaosan endovaskulaarista sulkua laajennettavalla balongilla väliaikaiseen vuotokontrolliin, jolloin voitetaan aikaa lopulliseen vuodon tukkimiseen embolisaation avulla.

C-tyypin lantionmurtumien sisäinen kiinnitysmenetelmä, lantiorenkaan kiinnitys edestä levyin sekä takaa ruuvein tai levyin, osoittautui luotettavaksi. Saavutettu asento säilyi seurannassa erinomaisena tai hyvänä 90%:ssa tapauksista. Leikkauksessa saavutettu murtuman hyvä asento korreloi hyvään neurologiseen toipumiseen ja toiminnalliseen tulokseen. Epäanatominen leikkaustulos tai murtuman uudelleen siirtyminen siten, että lopullinen siirtymä oli yli 5 mm, ennusti huonompaa toiminnallista lopputulosta. Merkittävin toimintakykyä rajoittava tekijä aiheutui lantion alueen hermopunosvauriosta. Tulokset tukevat käsitystä, jonka mukaan C-tyypin vammoissa tulee korjata ja kiinnittää kaikki murtumat lantiorenkaan etu- ja takaosassa, jolloin saavutetaan parempi anatominen tulos ja samalla parempi lantiorenkaan kokonaistukevuus.

Ristiluun H-tyypin murtuma, johon liittyy selkärangan ja lantiorenkaan irtoama toisistaan, on harvinainen lantion takaosan alueen vammakokonaisuus. Tutkimuksessa käytetty lannerangan ja lantion välinen kiinnitysmenetelmä (lumbopelvinen kiinnitys) osoittautui luotettavaksi kaikissa tapauksissa. Lantiohermopunoksen (alaraajojen osittainen halvaus) ja ristiluuhermojen vammat (ns. kauda equina syndrooma) ovat tähän vammatyyppiin liittyen yleisiä. Hermovaurion korjaantuminen ja kokonaistoipumisen ennuste oli riippuvainen ristiluun poikittaisen murtuman siirtymän asteesta. Hermovaurio oli vaikeampiasteinen ja toipumistulos huonompi, mikäli siirtymä ensimmäisessä kuvauksessa oli yli ristiluun paksuuden, kun tuloksia verrattiin siihen potilasryhmään, jolla siirtymä oli osittainen. Hyvä leikkauksessa saavutettu asento kaikissa ristiluun murtumalinjoissa oli yhteydessä parempaan toipumisennusteeseen. Poikittaisen ristiluumurtuman luokittelu siirtymän asteen mukaan osittain ja täydellisesti dislokoituneisiin murtumiin on käyttökelpoinen arvioitaessa tähän vammatyyppiin liittyvää neurologista toipumista leikkaushoidon jälkeen. Lisäämällä alaluokat Roy-Camille luokituksen 2 ja 3 tyypin murtumiin, voidaan parantaa hoidon suunnittelua ja hoitotuloksen ennustamista.

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

The present thesis is based on the following original publications, which will be referred to in the text by their Roman numerals (I-IV):

I   **Lindahl J, Hirvensalo E, Böstman O, Santavirta S**. Failure of reduction with an external fixator in the management of injuries of the pelvic ring: Long-term evaluation of 110 patients. *J Bone Joint Surg Br* 1999;81-B:955-962.

II   **Lindahl J, Handolin L, Söderlund T, Porras M, Hirvensalo E.** Angiographic embolization in the treatment of arterial pelvic hemorrhage: Evaluation of prognostic mortality-related factors. *Eur J Trauma Emerg Surg* 2013;39:57–63.

III   **Lindahl J, Hirvensalo E.** Outcome of operatively treated type-C injuries of the pelvic ring. *Acta Orthop* 2005;76:667-678.

IV   **Lindahl J, Mäkinen TJ, Koskinen SK, Söderlund T.** Factors associated with outcome of spinopelvic dissociation treated with lumbopelvic fixation. *Injury* 2014;45:1914-1920.

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ABBREVIATIONS

3D	three-dimensional
AIS	abbreviated injury scale
AO	arbeitsgemeinschaft für osteosynthesefragen
AP	anterior-posterior
AIIS	anterior inferior iliac spine
ASIS	anterior superior iliac spine
BE	base excess
CI	confidence interval
CT	computer tomography
DC	dynamic compression
EPP	extraperitoneal pelvic packing
ER	emergency room
FAST	focused abdominal sonography for trauma
GCS	Glasgow coma scale
Hb	hemoglobin level
HR	heart rate
ISS	injury severity score
MAST	medical anti-shock trousers
MOF	multiple organ failure
NISS	new injury severity score
NPWT	negative pressure wound therapy
OR	odds ratio
ORIF	open reduction and internal fixation
OTA	Orthopaedic trauma association
PASG	pneumatic anti-shock garment
pH	acid concentration
plat	platelets
POS	pelvis outcome scale
PRAF	pelvic ring and acetabular fractures
PRBC	packed red blood cells
PSIS	posterior superior iliac spine
REBOA	resuscitative endovascular balloon occlusion of the aorta
RR	respiratory rate
RTS	revised trauma score
SBP	systolic blood pressure
SP	symphysis pubis
SSI	surgical site infection
TAE	transcatheter angiographic embolization
tromb	thrombosytes
TT	thromboplastin time

1. INTRODUCTION

Unstable pelvic ring disruptions are relatively rare injuries, but they constitute a major cause of death and disability in high-energy polytrauma patients (Slätis and Huittinen 1972, Rothenberger et al. 1978, Hauschild et al. 2008, Papakostidis et al. 2009). High-energy pelvic ring disruptions are frequently associated with multiple concomitant injuries. In those cases, hemorrhage, head injury, pelvic soft tissue trauma (open fractures with or without rectal or vaginal injuries), and primary system complications contribute to the high mortality rates (Mucha and Welch 1988, Burgess et al. 1990, Tscherne and Regel 1996, Holstein et al. 2012). However, pelvic fracture-associated urinary tract injuries and closed Morel-Lavallée degloving soft tissue injuries do not influence acute mortality, instead they may contribute later morbidity (Lynch et al. 2005).

Pelvic fracture management has undergone a remarkable evolution during the last four decades. Nevertheless, successful treatment of pelvic fractures remains one of the most challenging clinical problems associated with the management of blunt trauma patients. The last decades have been a time of rapid progress in the control of pelvic fracture-related mortality and morbidity (Hauschild et al. 2008). A better understanding of the anatomic features of these fractures, and an awareness of potential major, exsanguinating arterial hemorrhage have led to multidisciplinary approaches for controlling bleeding and temporarily stabilizing the pelvic ring (Flint and Cryer 2010).

In the late 1970s, anterior external fixation devices became popular in the management of unstable pelvic ring injuries (Slätis and Karaharju 1975, Gunterberg et al. 1978, Slätis and Karaharju 1980, Lansinger et al. 1984). Prior to that, most pelvic fractures were managed non-operatively with extended bed-rest, closed reduction, a pelvic sling method, and skeletal traction (Holdsworth 1948, Peltier 1955). Early results with anterior external fixation frames were better than the results with conservative treatment; thus, the frames were widely used for temporary and definitive pelvic stabilization, until the 1990s. However, biomechanical and clinical studies showed that these frames had limitations, when used for the most unstable pelvic injuries (Mears and Fu 1980, Wild et al. 1982, Kellam 1989, Tile 1995).

Due to the high risk of hemorrhage, major pelvic fractures are among the most serious skeletal injuries, and they account for substantial mortality (Dyer and Vrahas 2006). In patients with multiple injuries that include pelvic ring disruption, exsanguinating retroperitoneal bleeding is the major cause of early death (Cryer et al. 1988, Ertel et al. 2000, Papakostidis and Giannoudis 2009, Holstein et al. 2012). Treatment is limited by the lack of a single parameter or test for detecting hemorrhage. Several general risk factors have been found to predict major hemorrhage and mortality, but none of these parameters are sufficiently specific to identify patients that are at the greatest risk of death.

The overall aim of surgical treatment for unstable pelvic ring injuries is to restore the pelvic anatomy, thus allowing normal function with a low rate of complications. It is difficult to evaluate the efficacy of surgical stabilization of the pelvic ring based on published long-term studies, because

different treatment concepts have been used and the majority of studies used non-comparable evaluation parameters. Additionally, no standardized measurement instrument exists to analyse the clinical and radiological data acquired for assessing pelvic ring injuries. In a systematic review of the English literature over the last 30 years, Papakostidis et al. (2009) concluded that "the current literature is insufficient to provide clear evidence for clinical decision-making in regards to the optimal treatment of unstable pelvic ring injuries".

H-shaped sacral fractures with spinopelvic dissociation are very rare, high-energy injuries. They are associated with deficits in the lumbosacral plexus and cauda equina (Roy-Camille et al. 1985, Schildhauer et al. 2006, Robles 2009). Historically, the treatment was non-operative, and the results were far from satisfactory. A well-designed treatment protocol for these injuries does not exist. The management and timing of interventions for this injury type have been variable (Robles 2009). Because the management of these injuries is one of the great challenges faced by orthopaedic trauma surgeons, it is crucial to evaluate outcomes and identify possible prognostic factors that can further the development of treatment strategies.

This doctoral thesis was initiated to investigate the outcomes of acute and definitive management strategies for unstable pelvic ring injuries. The first study investigated the radiological and functional results of treating type B and C pelvic injuries with an anterior compression external fixation frame. The second study focused on identifying factors for early predictions of mortality-related outcome and prognosis in patients with pelvic fracture-related arterial bleeding that were treated with transcatheter angiographic embolization (TAE). The third study investigated the outcomes of unstable type C pelvic fractures treated with standardized closed or open reduction and internal fixation methods. The fourth study evaluated outcomes and identified prognostic factors for operatively-treated, H-shaped sacral fractures with spinopelvic dissociation.

2. REVIEW OF THE LITERATURE

2.1. Epidemiology

Trauma is a worldwide problem that affects all nations and people (Kauvar and Wade 2005). Traumatic injuries account for 10% of global mortality (Murray and Lopez 1997). Trauma is the leading cause of death in young people (1 to 34 years) and the fifth leading overall cause of death in the USA (Holcomb 2004). Among lethal traumatic injuries, brain injury and hemorrhage are the leading overall causes of death; these conditions account for 40-50% and 30-40% of fatalities, respectively (Sauaia et al. 1995). A recent trauma registry-based study suggested that patients with multiple-traumas that included a pelvic fracture had an elevated risk of death from massive bleeding and brain injuries (Holstein et al. 2012). Uncontrolled hemorrhage is the leading cause of potentially preventable death (Holcomb 2004). Despite advances in management strategies, techniques, drugs, and devices, hemorrhage control remains a major problem in emergency medical care – worldwide.

Pelvic ring disruptions are relatively uncommon injuries and account for approximately 1% of fractures that require hospitalization among people ≥ 16 years in Finland (Somersalo et al. 2014). The reported incidence of pelvic fractures is 17-35 per 100.000 individuals per year in the general population (Melton et al. 1981, Ragnarsson and Jacobsson 1992, Lüthje et al. 1995, Court-Brown and Caesar 2006, Balogh et al. 2007). Among patients with multiple-traumas, up to 25% have pelvic ring injuries (Ragnarsson and Jacobsson 1992, Giannoudis et al. 2007, Matewski et al. 2008), which also are a significant source of mortality and morbidity (McMurtry et al. 1980, Gilliland et al. 1982). High-energy and low-energy injuries are equally frequent among hospital admissions (Balogh et al. 2007). During the past few decades, the rate of osteoporotic pelvic fractures in the older population has increased consistently (Kannus et al. 2000, Tosounidis et al. 2010). There are lower incidences of stress fractures, which commonly occur in athletes and in older people, and avulsion fractures, which typically occur in adolescents and children (Hauschild et al. 2008). Spinopelvic dissociation is a rare injury, but no data are available on the incidence of this injury.

2.2. Important anatomic considerations

A good knowledge of the anatomy and biomechanics of the pelvis is essential for adequate assessment and management of patients with pelvic injuries. The pelvis can be divided into the so-called 'false pelvis' and the 'true pelvis'. The false pelvis lies above the plane of the pelvic brim, the linea terminalis, and it can be considered part of the abdominal cavity. The true pelvis, distal to the plane of the pelvic brim, is formed by osseous and ligamentous walls, but it is open on the upper and lower ends. A layer of extraperitoneal fatty tissue contains the vascular and neural structures that supply the pelvic viscera and lower extremities. The true pelvis harbours the major visceral structures, including the bladder, sigmoid colon, rectum, internal reproductive organs in women and portions of the lower urinary tract in men.

Bony and ligamentous structures

The bony pelvis is a ring structure that comprises three bones: the sacrum and the pair of innominate bones. These three bones are held together by extremely strong ligaments. The innominate bones are formed by the fusion of three separate centres of ossification, the ilium, the ischium, and the pubis. These ossification centres meet at the triradiate cartilage, which fuses by 16 years of age (Tile 1995). The sacrum is a kyphotic structure, with a sagittal angulation from 0 to 90 degrees (Robles 2009). Stability is an essential anatomic feature of the pelvis. Major traumatic forces on the pelvis are needed to cause significant disruptions (Dalal et al. 1989, Eastridge et al. 2002).

The sacrum is composed of five fused sacral segments (Olson and Pollak 1996), but this number is variable among individuals (Rengachary 1994). The lumbosacral area has the highest degree of numerical variation in the axial skeleton. Occasionally, six segments may be included, due to sacralization of the L5 vertebra into the sacrum, either unilaterally or bilaterally. The sacrum is like the keystone of an arch; it transmits weight from the lumbar spine through the sacroiliac (SI) joints to the acetabulum (Tile 1955). Because the lumbosacral junction is located anterior to the SI-joint, the body weight transmitted to the superior surface of the sacrum acts as a rotary force, with an axis centred on S2; this force, causes the sacral promontory to tilt forward and the apex to tilt backward (Rengachary 1994).

The stability of the pelvic ring is based on the major pelvic ligaments, because the bony pelvis has no inherent stability. The SI-joint is a long articulation that extends from the first to the second sacral segments. Posteriorly, the SI-joints are stabilized by the posterior, interosseous, and anterior sacroiliac ligaments (Solonen 1957). The interosseous and posterior ligaments are thought to be the primary stabilizing ligaments of the SI-joint (Olson et Pollak 1996) and the strongest ligaments of the pelvis (Robles 2009). Furthermore, stability is increased inferiorly by the sacrotuberous and sacrospinous ligaments, which connect the sacrum to the tuber and spine of the ischium, respectively (**Fig. 1**). The sacrotuberous ligament originates in three locations and forms a strong ligamentous attachment at the medial border of the ischial tuberosity. The thinner sacrospinous ligament divides the posterior pelvis space into the greater sciatic foramen and the lesser sciatic foramen. In adults, the SI-joint is an essentially immobile structure (Robles 2009).

At the lumbosacral junction, the pelvis is secured to the axial skeleton by a strong intervertebral disc and bilateral iliolumbar ligaments. When the tip of the fifth lumbar transverse process is avulsed, it is considered as a sign of a pelvic ring injury that is vertically unstable, because the iliolumbar ligament attaches the tip of the fifth lumbar transverse process to the iliac crest (Olson and Pollak 1996).

Anteriorly, the pubic symphysis unites the opposing bony surfaces of the pubic bones by a fibrocartilaginous interpubic disc, reinforced superiorly and anteriorly by dense ligamentous fibres, and inferiorly by the arcuate pubic ligament (Olson and Pollak 1996). Additional anterior support is provided by the inguinal ligaments and anterior abdominal wall, but the biomechanical contributions of these anatomical structures are poorly understood.
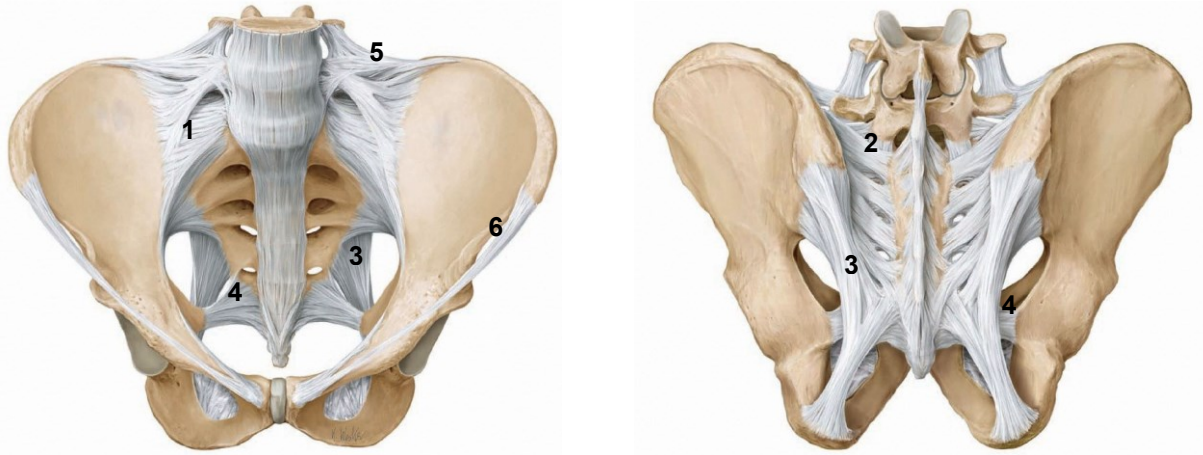
Figure 1. Ligaments of the pelvic ring. (1) anterior sacroiliac ligament, (2) posterior sacroiliac ligament, (3) sacrotuberous ligament, (4) sacrospinous ligament, (5) iliolumbar ligament, and (6) inguinal ligament (*Schuenke et al. Thieme Atlas of anatomy, general anatomy and musculoskeletal system. New York: Thieme Medical publishers, Inc., 2007*).

Vascular structures

Pelvic fracture-related hemorrhage can originate from the arteries and veins of the internal or external iliac systems, or from the presacral venous blexus. The presacral venous plexus is located just anterior to the sacrum and SI-joints, and therefore, they are subject to injury in fractures that affect the posterior sacroiliac complex. The internal iliac artery is the main artery that supplies the intra-pelvic structures. This artery, which is about 4 cm long, arises from the common iliac artery above the pelvic brim (linea terminalis) at the same level as the lumbosacral intervertebral disc, and anterior to the lateral sacrum. It then descends to the upper margin of the greater sciatic foramen (**Fig. 2**) where it divides into its main branches in the true pelvis (Williams and Warwick 1980). Severe trauma to the pelvis may disrupt the main internal iliac artery (O'Neill et al. 1996), the common iliac artery, or the external iliac artery (Rothenberger et al. 1978, Carrillo et al. 1999). Damage to the superior gluteal artery, the largest branch of the internal iliac artery, is a common cause of massive hemorrhage. Because this artery courses through the upper part of the greater sciatic foramen, it is prone to damage from traumas that injure of the SI-joint (**Fig. 2**). In the true pelvis, important bleeding can originate from the obturator artery, which runs along the lateral wall of the pelvis (the quadrilateral surface of the acetabulum) and enters the obturator foramen. Also, several other branches of the iliac arteries may be a potential source of arterial bleeding associated with pelvic fractures (O'Neill et al. 1996).

The veins follow the course of the arteries through the pelvis. A thin-walled, presacral venous plexus is located anterior to the sacrum, and when damaged, the escaping venous blood often passes into the retroperitoneum. Normally, in these situations, there is no need for surgical bleeding control procedures. However, rupture of the main iliac vein due to blunt pelvic trauma is difficult to diagnose, because bleeding weins do not show up on angiograph (Kataoka 2005). A diagnosis can be made based on pelvic venography, but this technique is seldom used during the initial resuscitation

or during emergent laparotomy when continuous venous bleeding is observed from a ruptured ret-roperitoneum in the pelvis. Bleeding from the internal iliac vein is often controllable with pelvic packing (Henry 1997), or with an endovascular stent placement (Kataoka 2005). Massive venous bleeding might occur more frequently than generally acknowledged (Suzuki et al 2009a).
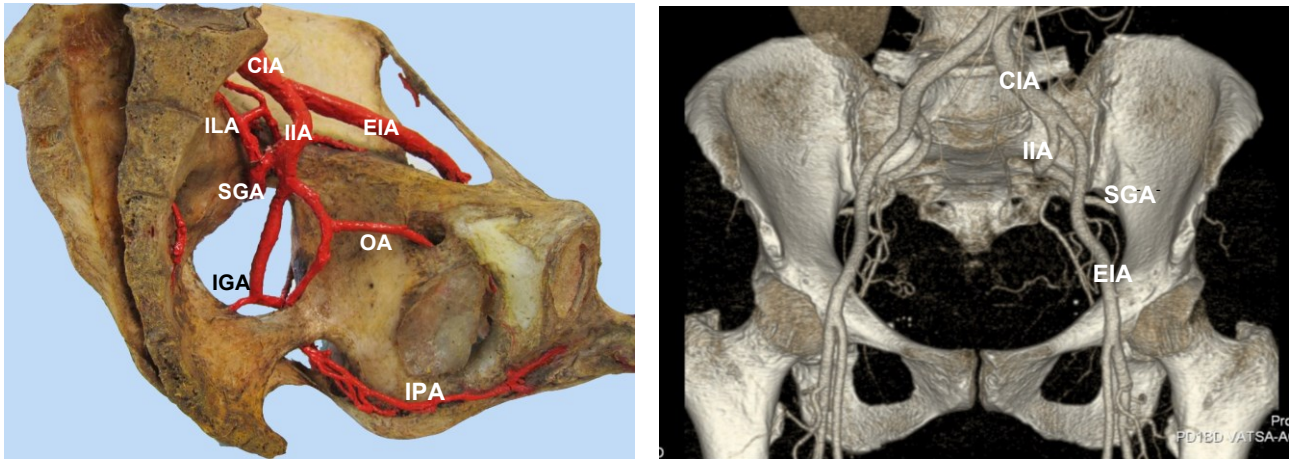
Figure 2. The common, internal and external iliac arteries and their main branches. (CIA) common iliac artery, (ILA) iliolumbar artery, (IIA) internal iliac artery, (EIA) external iliac artery, (SGA) superior gluteal artery, (IGA) inferior gluteal artery, (OA) obturator artery, and (IPA) internal pudendal artery.

Neural structures

The involvement of lumbar and sacral nervous plexus injuries has important influences on the re-covery and outcome of patients with unstable pelvic ring injuries. The lumbar and sacral nerve plexuses are formed by the ventral rami of the T12-S4 spinal nerves. The lumbar plexus lies in front of the transverse processes of the lumbar vertebrae. It is formed by the ventral rami of the first three lumbar nerves and branches of T12 and L4 nerves. The femoral nerve, the largest branch of the lumbar plexus (L2, L3, L4, dorsal divisions), descends through the substance of the psoas major muscle and passes behind the inguinal ligament to enter the thigh (Williams and Warwick 1980). The obturator nerve (L2, L3, L4, ventral divisions) descends through the psoas major and passes behind the common iliac vessels. Then, it runs down and forward, along the lateral wall of the pel-vis (quadrilateral surface), passing above and in front of the obturator vessels, to enter the obturator foramen and the thigh. The femoral and obturator nerves are only occasionally injured. The lateral femoral cutaneous nerve (L2, L3) emerges from the lateral border of the psoas major, crosses the iliacus muscle obliquely, running towards the anterior superior iliac spine (ASIS), and passes be-hind or through the inguinal ligament. It supplies the skin of the anterior and lateral parts of the thigh.

The sacral plexus is formed by six nerve roots from the lumbosacral segments: L4, L5, and S1 to S4. A branch of the L4 root crosses the L5 transverse process and the L5 root crosses the anterosu-perior border of the S1 vertebral body (sacral ala); these nerves join to form the lumbosacral trunk. The sacral nerves are located in the sacral canal; they enter the pelvic retroperitoneum via the sacral foramina. The dural sac ends blindly at the S2 level (Rengachary 1994). The first four ventral rami

of sacral nerves unite with the lumbosacral trunk in the true pelvis to form the sacral plexus. All the main branches of the sacral plexus leave the pelvis through the greater sciatic foramen, except four: the muscular branches, which run to the piriformis, levator ani, and coccygeus muscles, and the pelvic splanchnic nerve (S2, S3, S4). The sacral plexus ends in two terminal branches, the sciatic nerve (L4, L5, S1, S2, S3) and the pudendal nerve; also, it branches to many collateral nerves, including the superior gluteal nerve (L4, L5, S1) and inferior gluteal nerve (L5, S1, S2). The pudendal nerve (S2, S3, S4) provides sensory innervation to the external genitalia and supplies the perineum, including the external anal sphincter (S4).

In the retroperitoneum, the paired lumbar sympathetic trunk descends along the lumbar vertebrae bodies, cross behind the common iliac vessels, and enter the pelvis, where they become continuous with the sacral sympathetic trunk on the ventral surface of the sacrum (Rengachary 1994). The parasympathetic fibers that provide motor innervation to the detrusor muscle of the bladder run through the pelvic splanchnic nerves. Sympathetic fibres play a minor role in normal micturition; they are thought to come into play when the bladder is overstretched (Rengachary 1994).

2.3. Initial assessment

Clinical assessment

Early management of trauma patients must include a proper diagnosis of all the injuries. The diagnosis of a pelvic injury requires a high index of suspicion, particularly when the patient is unconscious or uncooperative. Assessment of the degree of pelvic instability must always begin with a careful history and physical examination.

Injury mechanism. Knowing the mechanism of injury provides a better understanding of the possible forces that may have impacted the pelvis (Cryer et al. 1988). Considerable force is needed to break the solid structure of the pelvic ring in younger patients. Thus many patients with pelvic ring fractures are polytraumatised, and they present with multiple associated injuries (Tscherne and Regel 1996, Giannoudis et al. 2007). Low-energy fractures are typically observed either in older patients that have fallen from a standing position, or in younger patients, that have sustained an avulsion in a tendon-bone complex of the pelvis (e.g., the ASIS, the anterior inferior iliac spine [AIIS], or the ischial tuberosity), during a sport activity (Pennal et al. 1980).

Physical examination. A physical inspection is crucial, because contusions, abrasions, scrotal swelling, and hematomas can provide additional information about the direction and magnitude of the forces involved and any contiguous structures that may have been injured. The Destot sign, a superficial hematoma above the inguinal ligament in the groin, over the scrotum or perineum, or in the upper thigh, may indicate a pelvic fracture (Failinger and McGanity 1992). Any lacerations should be examined, because they may indicate possible open fractures. A rotational deformity of the pelvis or lower extremity and a leg length discrepancy, without an obvious fracture to the long bones, are signs of a displaced pelvic ring (Pennal et al. 1980).

Palpation may reveal crepitus or an abnormal motion in the hemipelvis, indicative of instability. Bimanual compression and distraction of the iliac wings might reveal pain as a first sign of pelvic fracture. However, pelvic manipulation should be performed gently to avoid causing further pain to the patient; moreover, pelvic manipulation is unnecessary when an initial pelvic AP radiograph shows a displaced, unstable fracture. Rectal and vaginal examinations should be performed whether occult or frank bleeding is present from these structures, and an open fracture is suspected. Urethral and bladder injuries are suggested by the presence of meatal blood, an inability to urinate, and when the prostate is not palpable in a rectal examination. Degloving soft tissue injuries (Morel-Lavallée injuries) in the lumbosacral or other pelvic regions should be noted (Slack 1952, Kottmeier et al. 1996). The neurologic status of the lower extremities and the perineal area should be recorded.

Radiologic assessment

Plain radiography. The anteroposterior (AP) pelvic radiograph is the principal diagnostic tool and gold standard for assessing patients with suspected pelvic injuries. An AP pelvic radiograph is mandatory for the initial assessment in the emergency evaluation, and it provides the diagnosis. Inlet and outlet projections, as described by Pennal et al. (1980), have been used to obtain more information on anterior or posterior displacement and on cranial or caudal displacement of the pelvic ring. The inlet view is best for examining the continuity of the pelvic ring, AP displacement, and rotational deformities; the outlet view is best for examining vertical displacement and the sacral foramina. The lateral view of the sacrum is useful for identifying transverse sacral fractures.

Computer tomography. Computer tomographic (CT) scans provide sequential cross-sectional information about pelvic injuries. CT is very sensitive for detecting pelvic fractures and identifying associated injuries that often accompany the pelvic fracture. CT scans are best for delineating the posterior anatomy, and thay are extremely useful for identifying injuries of the sacroiliac complex, the sacrum, SI-joint, or iliac wing (Olson and Pollak 1996). CT is also useful as an adjunct in defining associated acetabular fractures (Gill and Bucholz 1984). Morover, CT is very valuable for assessing of pelvic stability. CT images clearly indicate whether a posterior pelvic injury is impacted and stable or disrupted and unstable (Tile 1995). An anterior opening combined with posterior apposition of the SI-joint indicates external rotation instability; in contrast, complete separation of the SI-joint surfaces, from anterior to posterior, indicates disruption of the strong posterior interosseous ligaments and vertical and rotational instability.

3D CT. Three-dimensional image reconstructions based on CT scans of the pelvis provide considerable information on the location and stability of pelvic fractures. 3D CT enhances the understanding of each fracture lines and the separate fragments by simulating the gross anatomy of the injured pelvis. In particular, rotational deformities and displacements of the pelvis are best visualized with 3D CT. Pelvic AP radiography and CT with 3D image reconstructions will confirm the type of pelvic injury, the presence or absence of instability, and the degree of each displacements. It is necessary to acquire 3D CT images prior to a definitive surgical treatment of an unstable pelvic fracture. 3D CT facilities are currently available in most trauma centres; therefore, oblique pelvic inlet and outlet views are no longer essential for diagnostics or for preoperative planning.

Whole-body CT. Time is a crucial factor for the outcome of multiply injured patients. Chest radiography, AP pelvis x-ray, cervical spine radiography, and focused abdominal sonography for trauma (FAST) are recommended during the initial assessment (ATLS), but they may not be able to determine the presence of severe or life threatening injuries. A multislice spiral CT can substantially reduce the time required for imaging results. Currently, this whole-body scanning technique can collect data on the whole torso in less than one minute (pure scanning time). The whole process, including a body scout view, examination planning, contrast application, and the actual scanning requires less than seven minutes (Kanz et al. 2004). However, it remains controversial whether to implement early use of the multislice spiral CT in patients that are hemodynamically unstable due to blunt trauma. Patient instability is considered a contraindication for an early whole-body scan (Leidner and Beckmann 2001). However, some clinicians use it when hemodynamic stability can be achieved with less than 2000 ml infusions (Willmann et al. 2001), and others use it for all patients with trauma after completing the FAST and chest x-ray exams (Kanz et al. 2004). A recent study based on a European Trauma Registry suggested that improved survival was associated with the incorporation of whole-body CT imaging in the initial phase of resuscitating patients with severe injuries (Huber-Wagner et al. 2009).

Contrast enhanced CT. Contrast enhanced trauma CT is performed to detect active arterial bleeding in the retroperitoneal space, and to assist early detection of potential sources of hemodynamic instability (Cerva et al. 1996, Stephen et al. 1999). Although evidence of contrast extravasation on a CT scan may suggest significant vascular injury, not all patients require invasive interventions such as TAE or extraperitoneal pelvic packing (EPP), to control the hemorrhage (Diamond et al. 2009). However, the absence of a pelvic hematoma or contrast blush on a CT scan does not rule out active pelvic arterial bleeding (Brown et al. 2005).

Detection of injuries to the lower urinary tract. Although CT is commonly used in the initial evaluation of patients that sustain high-energy blunt traumas, a urethral injury can be assessed and classified more effectively with urethrography. When resistance is encountered in placing a bladder catheter, a retrograde urethrogram is performed. Cystograms reveal intra- and extraperitoneal bladder ruptures (Chapple et al. 2004, Gomez et al. 2004, Lynch et al. 2005).

Radiography and CT in spinopelvic dissociations. AP pelvis radiography and CT scans reveal the vertical sacral fracture lines. However, the diagnosis of traumatic spinopelvic dissociations is often missed or delayed, due to the difficulty in imaging the upper sacrum and the transverse sacral fracture component. Angulation of a fractured sacral segment can produce a paradoxical inlet view of the upper sacrum on the standard AP pelvic radiograph (Nork et al. 2001). Delayed diagnosis is avoided by high clinical suspicion, early lateral sacral radiographs, and pelvic CT-based sagittal image reconstructions.

2.4. Pelvic fracture classification

Classification systems are typically descriptive, based on anatomy, or they focus on the mechanism of injury or on pelvic stability (Pennal et al. 1980, Bucholz 1981, Young et al. 1986, Tile 1988, Tile 1995). Historically, pelvic fractures were simply classified as either stable or unstable, based on physical findings and radiologic appearances (Trunkey et al. 1974). Slätis and Huittinen (1972) compared high- and low-energy pelvic injuries. The degree of pelvic stability can typically be suspected from history alone (Pennal et al. 1980). The pelvic disruption associated with a simple fall in an older patient is quite different from the high-energy injury associated with a major motor vehicle accident or a fall from great height.

An isolated anterior fracture of the pelvic ring is uncommon. When such a fracture is detected, a posterior disruption or some sign of compression should be sought. The basic rule is that, when the pelvic ring is disrupted in one place, there is an injury in another portion of the ring (Tile 1988). A radioisotope bone scanning study by Gertzbein and Chenoweth (1977) showed that undisplaced fractures of the pubic rami were invariably accompanied by a second injury located in the sacroiliac area. This second injury might be a fracture, a torn ligament, or a disrupted ligament attachment. Bucholz (1981) confirmed the presence of a posterior lesion in all cases, in a study of post-mortem material. Exceptions to this rule are spinopelvic dissociations without an anterior injury, transverse sacral fractures below the SI-joint level, avulsion fractures, and isolated iliac wing fractures.

2.4.1. Pelvic ring injuries

Pennal et al. (1980) first defined typical force vectors and their resulting pelvic fracture patterns. He showed that typical forces tended to open the pelvis like a book, collapse it toward the midline, or cause a vertical translation. These forces were called, respectively, anterior posterior compression (APC), lateral compression (LC), and vertical shear (VS). The term VS implies only one direction of displacement, but when this type of high-energy injury occurs, the hemipelvis may displace in several directions; therefore, the term "completely unstable" is more descriptive. Radiological analysis of all pelvic fracture patterns can provide information about the trauma mechanism (Lefaivre et al. 2015). The pelvic ring may fail due to injuries to the bone, the ligaments, or both types of structures.

Mechanism of injury classification (Young-Burgess)

The Young-Burgess classification system is based on the injury mechanism (Young et al. 1986). This classification divides injuries into four categories. The first two are the APC and LC categories, which are subdivided into three subgroups (I, II, and III), based on increases in injury severity produced by increases in force magnitude (Burgess et al. 1990). The third category is the VS pattern, which includes vertical and posterior displacements. This category includes a posterior ring injury that passes through the ilium, the SI-joint, or the sacrum, and an anterior injury through the SP or the pubic rami. The fourth category is the combined mechanical (CM) injury, which includes pathologies that result from a combination of forces and/or directions. The Young-Burgess classification is useful for predicting transfusion requirements (Manson et al. 2010).

Stability classification (Tile)

Tile's classification is based on a combination of the estimated direction of the major force vector and the degree of pelvic instability (Kellam et al. 1987, Tile 1988). According to the Tile system, pelvic ring fractures are graded into three types, A, B, and C, in order of increasing severity. Type A injuries are stable fractures. Type B injuries are rotationally unstable, but vertically and posteriorly stable. They may be caused by external rotary forces (open book injuries) or by internal rotary forces (lateral compression injuries). Type C injuries are complete disruptions of the posterior sacroiliac complex and the anterior part of the pelvic ring, due to vertical shear forces. This includes Malgaigne's fracture (1859) which consists of fractures in both pubic rami, combined with a fracture in the posterior pelvis.

Comprehensive classification

The comprehensive classification combines the Arbeitsgemeinschaft für Osteosynthesefragen (AO) classification of fractures of the long bones (Müller et al.1990) and the Orthopaedic Trauma Association's (OTA) classification system (Fracture and dislocation compendium 1996, Marsh et al. 2007) with the Tile classification. Through subgroups and qualifications, the comprehensive classification incorporates anatomy, the concept of pelvic stability, and concepts of mechanism of injury (Marsh et al. 2007).

Type 61-A stable injuries. Type A injuries are stable fractures, which fall into two categories. The first category includes fractures that do not involve the ring, which include avulsion fractures, fractures of the iliac wing, and isolated transverse fractures of the sacrum below the SI-joint level. The second category includes direct-blow fractures in the anterior arch; these involve the pubic rami, uni- or bilaterally, or the ramus on one side with an injury to the SP.

Type 61-B partially stable injuries. Type B injuries are divided into three subgroups (61-B1 to 61-B3). The *type B open book injury* (61-B1) is caused by APC force or, in some cases, by external rotation of the femora, which results in a disruption of the SP. As the force increases, tearing occurs in the pelvic floor ligaments and the anterior sacroiliac ligaments. The interosseous and posterior sacroiliac ligaments remain intact. The result is an unstable pelvis in external rotation, but no superior, posterior, or inferior migration of the hemipelvis occur; thus, relative vertical stability of the pelvic ring is maintained (Olson and Pollak 1996).

Experimentally, widening the SP by more than 2.5 cm is always associated with a disruption of the ligaments of the pelvic floor. In contrast, widening the SP by less than 2.5 cm does not cause concomitant disruption of the pelvic floor (Tile 1995). X-rays alone cannot be used to assess the degree of pelvic instability, because they only show pelvic alignment at one moment in time. Therefore, x-rays must be interpreted in conjunction with a clinical assessment.

In the *type B lateral compression injury* (61-B2), the hemipelvis is typically driven into an inward and upward rotation, which causes shortening and vertical displacement at the rami fracture site or disruption of the SP (overlap of the pubis). The posterior sacroiliac complex is typically impacted, but there is no vertical instability, because the posterior ligaments are intact. A lateral compressive

force may cause two types of injury. In one type, anterior and posterior lesions occur on the same side, and in the other type, displacements occur on opposite (contralateral) sides. The ligaments of the pelvic floor remain intact, which ensures vertical and posterior stability.

In the *bilateral type B injury* (61-B3) posterior ring injuries occur on both sides, and both are vertically stable.

Type 61-C completely unstable injuries. Type C injuries exhibit both rotational and translational instability. These high-energy injuries involve VS, major APC, or a combination of these force vectors. In this group of injuries, the pelvic floor soft tissue structures are torn. Type C injuries are often associated with injuries to the lumbosacral plexus and to vascular, genitourinary, and gastrointestinal systems. Injuries classified as type C, in the comprehensive classification, are comparable to those classified as VS and APC III in the Young-Burgess system (**Table 1**).

In type C1 injuries, the posterior injury is divided into three subgroups: 61-C1.1 is a fracture through the posterior ilium; 61-C1.2 may be a transiliac fracture dislocation of the SI-joint, a pure sacroiliac dislocation, or a trans-sacral fracture dislocation of the SI-joint; 61-C1.3 is a fracture through the sacrum. The last two groups are used to classify a bilateral posterior injury. The 61-C2 bilateral posterior lesion is vertically unstable on one side and stable on the other side; the 61-C3 lesion is unstable on both sides. All these type C fractures include anterior pelvic ring injuries, such as disruption of the SP, overlap of the SP, a unilateral fracture in a pubic ramus, bilateral fractures in the pubic rami, and fractures of uni-or bilateral pubic rami with a disruption of the SP.

Table 1. Comparison of the comprehensive AO/OTA and Young-Burgess classification systems.

Comprehensive AO/OTA	Young-Burgess
Type A stable	None
Type B partially stable	
- B1 open book	APC I, APC II
- B2 lateral compression	LC I, LC II
- B3 bilateral B injury	LC III
Type C completely unstable	VS, APC III

2.4.2. Sacral fractures

The Denis classification system is commonly used for categorizing sacral fractures (Denis et al. 1988). It divides sacral fractures into three zones: zone I fractures occur in the alar region; zone II fractures involve the sacral foraminal area, and zone III fractures occur in the vicinity of the central canal. Denis et al. (1988) found that a nerve root injury occurred in 5.9% of fractures lateral to sacral foramina, in 28.4% of transforaminal fractures, and in 56.7% of central canal fractures.

Transverse sacral fractures are uncommon injuries; they constitute 3 to 5% of all sacral fractures (Denis et al. 1988, Robles 2009). Isolated transverse sacral fractures located at the level of S3 or below do not result in instability of the pelvic ring. A transverse sacral fracture may involve zone III (spinal canal) in addition to Denis zones II and I. Therefore, transverse sacral fractures form a special kind of fracture type, which seldom fits one specific type of fracture described in the Denis classification (Robles 2009). Displaced transverse fractures might result in cauda equina deficits.

2.4.3. Spinopelvic dissociations

The spinopelvic dissociation is a rare, high-energy injury pattern located in the sacrum. It is characterized by bilateral vertical sacral fractures in conjunction with a transverse sacral fracture. Denis's system does not recognize the combination of bilateral vertical and transverse fracture lines that cause spinopelvic dissociation. This injury causes the spine and upper central segment of the sacrum to dissociate from the pelvic ring and caudal sacral segments. Roy-Camille et al. (1985) described the spinopelvic dissociation injury, but they classified only the transverse sacral fracture, not the bilateral vertical fracture components. Roy-Camille et al. divided transverse sacral fractures into three types, and later, Strange-Vongsen and Lebech (1991) added a forth type (Schildhauer et al. 2006). In this classification, type 1 is a flexion injury without translational displacement; type 2 is a flexion injury with partial anterior translational displacement of the caudal sacral segment; type 3 is an extension injury with complete posterior translational displacement of the caudal sacral segment (Roy-Camille et al. 1985); and type 4 is an axial loading injury with a segmentally comminuted S1 body (Strange-Vongsen and Lebech 1991). However, the type 4 fracture is a burst fracture of S1-S2 with bone retropulsion, not a true transverse sacral fracture (Robles 2009). Bilateral vertical sacral fractures associated with a transverse fracture might form the so-called H-, U-, or Y-shaped fracture patterns (Roy-Camille et al. 1985, Nork et al. 2001, Hunt et al. 2002, Tan et al. 2012).

2.5. Pelvic fracture-related bleeding

Major pelvic injuries are associated with a high risk of venous and arterial bleeding (Huittinen and Slätis 1973, Mucha and Welch 1988, Blackmore et al. 2006). The presence of hypotension (SBP < 90 mmHg) at the time of arrival was found to significantly increase mortality (**Table 2**). Pelvic fractures, however, may be caused by low- or high- energy trauma, and they may be an isolated injury or associated with additional injuries to other body regions. In patients that sustain polytraumas, the injury distribution and injury severity vary substantially, and hemodynamic instability may be caused by conditions other than hemorrhage. Approximately 10% of pelvic fractures among hospital admissions are characterized by hemodynamic instability (Eastridge et al. 2002).

Pelvic hemorrhage can be massive (O'Neill et al. 1996, Kataoka et al. 2005). It typically originates from an injured retroperitoneal presacral venous plexus (Henry et al. 1997, Sadri et al. 2005), directly from the cancellous bony surfaces and bony edges of the fracture lines (Huittinen and Slätis 1973, Sadri et al. 2005), or from pelvic arterial disruptions (Huittinen and Slätis 1973). The retroperitoneum is a closed space; thus, hemorrhage from a venous plexus eventually stops, when the

counter-pressure exceeds venous pressure (Henry et al. 1997), and the patient's coagulation status is maintained within acceptable limits (Durkin et al. 2006). The study by Huittinen and Slätis (1973) showed that death from hemorrhage is rare but when it does occur, it most often originates from an arterial source in the pelvic ring. In addition, nearly half of these patients have other sources of bleeding, often from a thoracic or abdominal injury (Papadopoulos et al. 2006).

In multiple-trauma patients with a pelvic disruption, exsanguinating bleeding remains the major cause of early death during the first 24-48 hours after trauma (Rothenberger et al. 1978, Gilliland et al. 1982, Cryer et al. 1988, Ertel et al. 2000, Smith et al. 2007, Papakostidis and Giannoudis 2009, Holstein et al. 2012). Treatment decisions during this time interval have significant influence on patient survival (Kregor and Routt 1999). Patients with arterial bleeding must be identified early to prevent further bleeding-related complications.

Identifying patients with major arterial hemorrhage after a blunt pelvic trauma might be difficult. There is no emergent parameter or single test for detecting hemorrhage. Assessments of bleeding require a complex, combined evaluation of the trauma mechanism, vital signs, and physiological parameters. The detection of external and internal bleeding sources is based on injuries found on the trauma CT scan and other secondary investigations, a need for blood product replacements, and the response to treatment (Rossaint et al. 2006). Pelvic fracture classifications have limited utility in predicting the risk of hemorrhage for individual patients (Sarin et al. 2005). Common scoring systems for assessing injury severity, such as the Injury Severity Score (ISS) (Baker et al. 1974), the New Injury Severity Score (NISS) (Osler et al. 1997), and the Revised Trauma Score (RTS) (Champion et al. 1989), are not sufficiently specific to be useful for the early diagnosis of bleeding.

The ideal emergency parameter for hemorrhage (a risk factor of mortality) should be available early, within the first 10 to 15 min. Several general risk factors have been found to predict major hemorrhage and mortality (**Table 2**), but none of the known general parameters is sufficiently specific to identify patients that are at the highest risk of death. Prognostic mortality-related risk factors should also be integrated into the management protocols.

Massive bleeding

The extent of a life-threatening injury is difficult to judge adequately. Spahn et al. (2007) defined massive bleeding in trauma patients as the loss of one blood volume within 24 hours or the loss of 0.5 blood volumes within three hours. To facilitate early recognition, Scandinavian guidelines defined massive bleeding due to trauma in the adult patient as a continuing need for pressure-driven intravenous fluid and blood component replacement (Gaarder et al. 2008). Massive bleeding is often caused by a combination of vascular injury and coagulopathy (Spahn et al. 2007).

Patients that are exsanguinating "in extremis" are at the greatest risk of death. This patient group is characterized by absent vital signs or severe shock with an initial systolic blood pressure <70 mmHg and/or they require mechanical resuscitation or catecholamines, despite more than 12 blood transfusions within the first two hours after admission (Gänsslen et al. 2012). Patients that receive massive blood transfusions exceeding 50 U have a low survival rate (Michelsen et al. 1989, Kivioja

Table 2. Factors predicting hemorrhage and mortality in blunt pelvic trauma patients.

Risk factor	Reference
A. Hemodynamic and laboratory parameters	
Systolic blood pressure (<90/100 mmHg)	Gilliland et al. 1982, O'Neill et al. 1996, Ertel et al. 2000, Starr et al. 2002, Sharma et al. 2008, Holstein et al. 2012
Pulse rate (100/130 or greater)	Ertel et al. 2000, Blackmore et al. 2006
Low hemoglobin concentration	Gilliland et al. 1982, Starr et al. 2002, Holstein et al. 2012
Hematokrit (30 or less)	Blackmore et al. 2006
Base excess	Starr et al. 2002
High blood lactate level	Ertel et al. 2001
Transfusion requirements	Gilliland et al. 1982, Smith et al. 2007, Sharma et al. 2008, Holstein et al. 2012
B. Patient-related aspects	
Age of the patient	Rothenberger et al. 1978, Mucha and Farnell 1984, Ertel et al. 2000, Starr et al. 2002, Smith et al. 2007, Sharma et al. 2008
Gender (male)	Holstein et al. 2012
C. Fracture-related aspects	
Pelvic fracture type	Rothenberger et al. 1978, Gilliland et al. 1982, Mucha and Farnell 1984, Cryer et al. 1988, Burgess et al. 1990, Magnussen et al. 2007, Sharma et al. 2008, Holstein et al. 2012
Mechanism of pelvic ring injury	Dalal et al. 1989, Burgess et al. 1990, Magnussen et al. 2007, Sharma et al. 2008
Degree of displacement of pelvic fracture	Blackmore et al. 2006, Sharma et al. 2008
D. Pattern and severity of injuries	
ISS	Gilliland et al. 1982, Mucha and Farnell 1984, Evers et al. 1989, Lunsjo et al. 2007, Smith et al. 2007, Hauschild et al. 2008, Sharma et al. 2008, Holstein et al. 2012
Revised Trauma Score (RTS)	Starr et al. 2002, Smith et al. 2007
Head injury	Gilliland et al. 1982
Glasgow Coma Scale (GCS)	Smith et al. 2007

et al. 1991). In general, the mortality rate for patients that require massive transfusions was reported to be approximately 50% (Phillips et al. 1987, Wudel et al. 1991, Hakala et al. 1998).

Life-threatening bleeding from pelvic or acetabular fractures in pediatric patients is even more rare (2.8%). Therefore, this population does not substantially contribute to the overall mortality (Tuovinen et al. 2011).

2.6. Emergency treatment of pelvic bleeding

Emergency treatment should focus on hemorrhage control and extensive shock therapy. However, upon admission, early detection of the major source of the hemorrhage responsible for shock is difficult (Hak 2004). Treatment of patients with pelvic fractures that are hemodynamically unstable remains controversial. Current trauma protocols are based on rapid control of external and internal bleeding; prevention of the lethal triad (acidosis, hypothermia, and coagulopathy); control of emergent laboratory parameters (e.g., blood hemoglobin, platelets, pH, base deficit, lactate, serum calcium); appropriate use of blood components; maintenance of tissue perfusion; and pharmacological treatment (Henry et al. 1997, Rossaint et al. 2006).

Initially, patients with a major pelvic ring injury that are hemodynamically unstable are evaluated to rule out ongoing intra-abdominal and intrathoracic hemorrhage (Olson and Pollak 1996). In combined pelvic and abdominal injuries, a grossly positive FAST and a hemoperitoneum detected in the trauma CT indicate the need for exploratory laparotomy. Emergency treatment includes closed pelvic ring reduction and provisional stabilization before, or simultaneous with, the laparotomy (Ghanayem et al. 1995, Cook et al. 2002). Once other sources have been excluded for persistent hemodynamic instability, efforts should address aggressive hemostasis of the pelvis (Mucha and Wells 1988, Evers et al. 1989, Smith et al. 2007).

2.6.1. Provisional stabilization of the pelvic ring

Various methods of provisional pelvic stabilization have been described to reduce hemorrhage. In the mid-1970s, the Medical Anti-Shock Trousers (MAST) or Pneumatic Anti-Shock Garment (PASG) was introduced (Batalden et al. 1974, Lilja et al. 1975). A randomized trial showed that these devices provided no benefit to survival (Mattox et al. 1989). In addition, several complications have been reported, like compartment syndrome of the abdomen or lower legs, and pressure sores (Aprahamian et al. 1989).

Closed reduction and stabilization of the pelvic ring decreases the volume and improves stability (Grimm et al. 1998, Gardner et al. 2009). Closure and mechanical stabilization of the pelvic ring might be performed with a pelvic binder (pelvic orthotic device) (Bottlang et al. 2002, Croce et al. 2007, DeAngelis et al. 2008, Spanjersberg et al. 2009, Tan et al. 2010), an anterior external frame (Wild et al. 1982, Gylling et al. 1985, Burgess et al. 1990, Latenser et al. 1991, Riemer et al. 1993, Ghanayem et al. 1995), or a posterior pelvic C-clamp (Ganz et al. 1991, Pohlemann et al. 2004),

depending on the type of pelvic ring injury, the local treatment protocol, and the resources available (Spahn et al. 2007).

Pelvic binders and external fixators can effectively tamponade non-arterial bleeding from bone edges and pelvic veins, but they do not stop arterial bleeding. It is thought that reducing the pelvic ring, restoring the pelvic volume, and providing temporary stabilization to the fracture and soft tissue injury can control pelvic hemorrhage through several mechanisms. Stabilizing the pelvic ring can prevent dislodgement of hemostatic clots. Reduction of the fracture surfaces slows bony bleeding, thus promoting clot formation and reducing blood loss. Also, pelvic fracture reduction diminishes the pelvic volume, which reduces the potential retroperitoneal space for blood accumulation, and thus, hemorrhage can be impeded from non-arterial sources (Evers et al. 1989, Burgess et al. 1990, Ghanayem et al.1995, Wolinsky 1997).

Biomechanical studies have shown that, in type C pelvic ring injuries, C-clamps are more effective than the standard anterior external fixators for achieving compression at the SI-joints (Alonso et al. 1996). On the other hand, a cadaveric study showed that, in type B open book injuries, an anterior external fixator and pelvic clamps were equally effective for reducing pelvic volume and pubic diastasis (Ghanayem et al. 1995). Currently, emergency indications for the use of a C-clamp are: a clinically unstable pelvic ring in association with hemodynamic instability; a complete interruption of the posterior ring (type C injuries); and a lack of patient response to resuscitation within the first 10 to 15 min after admission (Pohlemann et al. 2004).

2.6.2. Transcatheter angiographic embolization

Pelvic angiography and embolization was initially used to control arterial sources of intrapelvic bleeding in the 1970s (Margolies et al. 1972). Angiography can precisely identify the source of hemorrhage, and selective transcatheter angiographic embolization (TAE) can definitively treat arterial bleeding (Matalon et al. 1979, Panetta et al. 1985, Piotin et al. 1995, O'Neill et al. 1996, Cook et al. 2002, Tötterman et al. 2006). However, there is no clear consensus on the appropriate indication, timing, or order for applying angiographic interventions in pelvic fractures accompanied by exsanguinating retroperitoneal bleeding.

When angiography and embolization are performed early, within the first hours after admission, they seem to improve patient outcomes (Evers et al. 1989, Agolini et al. 1997, Eastridge et al. 2002). In combined pelvic ring and abdominal injuries, numerous investigators have recommended that laparotomy, when indicated, should be performed before TAE (Moreno et al. 1986, Evers et al. 1989, Yang and Iannacone 1997). However, Eastridge et al. (2002) reviewed 193 pelvic fractures and found that patients (n=4) that underwent angiography before laparotomy had better outcomes than patients (n=10) that underwent laparotomy first (mortality 25% and 60%, respectively).

It is generally believed that hemorrhage from the venous plexus will stop spontaneously, because increasing tissue pressure in the retroperitoneal space can provide tamponade (Henry et al. 1997). On the other hand, arterial hemorrhage can overcome a tamponade effect, and this condition can

lead to hypovolemic shock. The volume of the retroperitoneal space is large; it extends from the diaphragm to the true pelvis; thus, it can accommodate several litres of blood.

Several drawbacks have been associated with performing TAE. First, TAE can be time-consuming; also, transporting the patient to the angiography suite can be time-consuming; therefore, simultaneous treatment of associated injuries must be delayed. Second, TAE requires a skilled interventional radiologist; thus, this individual must be available 24 hours per day, which might be difficult to organize in small trauma units. Third, access to the femoral artery might be difficult, due to obesity, hypotension, or soft tissue injuries (Panetta et al. 1985, O'Neill et al. 1996). Finally, rare complications have been reported, such as hematoma at the puncture site, and pseudoaneurysm at the arterial puncture site (Cook et al. 2002).

Embolization of the internal iliac arteries were reported to cause ischemia and necrosis of the gluteal muscle, bladder wall, uterus, colon, and femoral head. In addition, complications include neurological defects, paresis of the lower leg, and impotence (Hietala 1978, Mucha and Welch 1988, Cook et al.2002, Tötterman et al. 2006). Some studies have reported recurrent bleeding after TAE; this condition requires ongoing blood product administration and re-embolization (Gourlay et al. 2005, Shapiro et al. 2005, Fang et al. 2009).

2.6.3. Surgical control of bleeding

The anatomy of the pelvis presents a challenge for maintaining surgical hemostasis (Henry et al. 1997). During massive retroperitoneal bleeding, it is difficult to achieve direct visualization of the main branch of the internal iliac artery. An operative ligation of the internal iliac artery is fraught with hazard (Seavers et al. 1964, Ravitch 1964, Hawkins et al. 1970, Rothenberger et al. 1978). Surgical exploration of the retroperitoneal hematoma releases existing tamponades, and small arterioles and veins may start bleeding anew (Hawkins et al. 1970, Scalea and Sclafani 2001). In addition, surgical exploration of the retroperitoneal hematoma increases the danger of infection (Stock et al. 1980, Tötterman et al. 2007, Papakostidis and Giannoudis 2009, Suzuki et al. 2009a).

In combined pelvic ring and abdominal injuries, when the retroperitoneal hemorrhage remains uncontrolled during the course of emergency laparotomy, pelvic packing should be undertaken as a damage control adjunct. Pelvic packing is the treatment of choice in cases of ruptured retroperitoneum and continual hemorrhage at the time of laparotomy. In a recent study, bilateral ligation of the internal iliac arteries and pelvic packing were used to control an expanding retroperitoneal hematoma that was encountered during an emergency laparotomy (DuBose et al. 2010). The overall mortality rate after this approach was 64.3% in a series of 28 patients with severe injuries.

Injuries to the main trunk of the common iliac artery and to the external iliac artery are uncommon (Rothenberger et al. 1978, O'Neill et al. 1996, Carrillo et al. 1999). This condition represents an exception to the general principles of managing bleeding from the internal iliac system. In this condition, the clinician should always attempt to repair the injury to the common iliac and external iliac

arteries, because the patient is at significant risk of critical ischaemia in the lower leg, which can result in limb loss (Green and Allen 1977, Henry et al. 1997).

2.6.4. Extraperitoneal pelvic packing

In the 1970s, the packing technique was utilized during laparotomies in pelvic fracture patients to control continual retroperitoneal hemorrhage through ruptured retroperitoneum (Hawkins et al. 1970, Flint et al. 1979). The early results of transperitoneal pelvic packing procedures were disappointing, probably due to loss of the tamponade effect in the pelvic retroperitoneum, and also due to late application of the pack (Papakostidis and Giannoudis 2009). Early surgical control of pelvic-fracture related hemorrhage with pelvic packing was employed by Riska et al. (1979), who used several different approaches to the pelvis. In their series of 42 patients with bleeding pelvic fractures, 12 patients (28.6%) died. Later, the concept of damage control surgery was extended to the control of massive pelvic hemorrhage with an extraperitoneal pelvic packing (EPP) technique (Pohlemann et al. 1995, Tscherne et al. 2000, Ertel et al. 2000, Ertel et al. 2001). The significant advantage of this technique was that the compression provided direct tamponade in the true pelvis. With this technique, tamponades are applied in the presacral and paravesical spaces, where most pelvic bleeding occurs (Suzuki et al. 2009a). During the past decade, more clinical studies have investigated the use of EPP (Smith et al. 2005, Tötterman et al. 2007, Cothren et al. 2007, Osborn et al. 2009, Suzuki et al. 2009a).

2.6.5. Aortic balloon occlusion

The use of endovascular techniques to manage severe injury has increased over the past ten years (Brenner et al. 2014). Resuscitative aortic occlusion with a balloon has been used to control intra-abdominal bleeding (Hughes 1958, Ledgerwood et al. 1976, Gupta et al. 1989, Avaro et al. 2011), renal vascular pedicle bleeding (Long et al. 2004), and more recently, massive pelvic bleeding in patients with pelvic injuries (Martinelli et al. 2010). The goal of temporary occlusion of the aorta is to increase central perfusion to the heart and brain in the setting of vascular injury and hemorrhagic shock.

In pelvic bleeding, the endovascular technique involves over-the-wire access to the iliac arterial system and placement of a working port in the femoral artery (Brenner et al. 2014). Once access is achieved, the balloon catheter is directed within the abdominal aorta, and placed distal to the renal arteries. The infrarenal balloon is inflated to occlude the aorta and to stop retroperitoneal arterial bleeding temporarily. A recent study in a porcine model showed that resuscitative aortic balloon occlusion increased central perfusion pressures with less physiologic disturbance than resuscitative thoracotomy with aortic cross-clamping (White et al. 2011). The use of endovascular therapies to manage life-threatening bleeding was associated with reduced morbidity and mortality compared to the traditional open surgery approach (Brenner et al. 2014).

2.7. Open pelvic fractures

The proximity of genitourinary structures (Niemi and Norton 1995) and the rectum to the osseous structures of the pelvic ring facilitates the intrusion of fracture fragments, which could compromise these visceral structures (Grotz et al. 2005). Open fractures are defined as injuries that incur a direct tract through the perineal or other skin laceration, the rectum, and the vagina to the fractured bone. An urgent diverting colostomy is indicated for rectal lacerations and for extended perineal soft tissue injuries that are not associated with rectal injuries (Hanson et al. 1991). Delaying a diverting colostomy has generated unfavourable results (Richardson et al. 1982). Patients with open fractures that include perineal or rectal wounds have lower survival rates (mortality 44%) than those without perineal lacerations (mortality 0%) (Jones et al. 1997).

The severity of the soft tissue injury is most reliably evaluated in the operation room. Open wounds are treated with surgical debridement to remove all necrotic tissue and jet lavage to remove foreign debris. A high percentage of patients with open pelvic fractures have sustained polytraumas; thus, external fixation is needed for immediate skeletal stabilization. A careful initial evaluation of the extent and degree of soft tissue injury provides information for determining the timing of surgical interventions, the type of definitive fracture fixation, the type of soft tissue coverage, and the prognosis. Patient resuscitation should first focus on saving life and limb, then, on providing a normal long-term functional outcome.

Definitive reconstruction and internal fixation of the pelvic ring can be performed after the patient is hemodynamically stabilized. Severe soft tissue injury with loss of muscle requires soft tissue reconstruction with vascularized rotational or vascularized free tissue (muscle) grafting. It is recommended that soft tissue reconstructions should be performed during the operation required for ORIF, or 1 to 3 days later. Depending on the severity and location of the soft tissue injury, the anterior bony injury to the pelvic ring might be treated either with an anterior external fixator or with internal fixation. Appropriate treatment of these complex injuries requires a clinical team that includes an orthopaedic trauma surgeon and a plastic surgeon.

Initially, patients should be protected with tetanus prophylaxis. Intravenous antibiotic therapy should be initiated promptly with a second-generation cephalosporin or clindamycin and an aminoglycoside (Gustilo et al. 1984, Alonso et al. 1996). In severely contaminated wounds, for example, in farm and railroad injuries, triple antibiotic coverage is recommended with the addition of metronidazole.

2.8. Associated injuries

Patients that sustain high-energy, blunt pelvic traumas are at high risk of multiple associated injuries.

2.8.1. Neurologic injuries

The lumbar and sacral nervous plexuses are at risk of injury due to their proximity to the bony pelvic structures and ligaments. Permanent nerve injury is a common cause of late sequelae following unstable pelvic ring disruptions. The overall prevalence of nerve injuries associated with pelvic trauma, including cases when nerve injury is temporary, is not well known. In a recent multicentre analysis, neurological long-term sequelae increased with the severity of pelvic ring injury. The incidence was 4% after type A, 11% after type B, and 17% after type C injuries (Dźupa et al. 2011). Among these, urological and sexual sequelae were present in 8% after type A and B injuries, an in 14% after type C injuries.

Huittinen and Slätis (1972) followed 68 patients with double vertical fractures of the pelvis (type C injuries) for 1 to 5 years after the accident. All patients had a vertically unstable posterior disruption of the pelvis, sacrum fractures and SI-joint injuries occurred at a ratio of 3:2. Thirty-one patients (46%) showed evidence of significant neurologic injury. The signs of neural damage were confined to nerve roots L4-S5. The severity of nerve injuries ranged from minor disturbancies to total paralysis and complete loss of sensation. In a subsequent post-mortem study, Huittinen (1972) found that lateral compression-type injuries tended to compress and entrap the sacral nerve roots; in contrast, vertically unstable type C injuries were more likely to stretch or avulse the ventral nerve roots.

Among sacral fractures, the fracture course was correlated to the rate of neurological deficits. Denis et al. (1988) found that, among fractures lateral to the sacral foramina (zone I), 5.9% included nerve injuries, typically a partial injury to the L5 nerve root. Among transforaminal sacral fractures (zone II), 28.4% included a neurological deficit, typically due to an injury to the ventral root of L5, S1, or S2. Central sacral fractures (zone III) had the highest prevalence (56.7%) of nerve injury. Nearly 80% of these deficits affected the bladder, bowel, and/or sexual function.

Up to 100% of sacral fractures with a spinopelvic dissociation result in a neurological injury. Bilateral vertical transforaminal sacral fractures are frequently associated with injuries to the L5 and S1 nerve roots, with varying severity (Schildhauer et al. 2006, Tan et al. 2012). The L4, L5, and S1 nerve roots can be injured when the sacrum undergoes vertical shear displacement. Displaced transverse sacral fractures result in cauda equina neurological deficits, with bladder and bowel dysfunction in 44 to 100% of patients (Schildhauer et al. 2006, Ayoub 2012, Tan et al. 2012).

A nerve injury may involve more than one nerve root, and it may be unilateral or bilateral, depending on the fracture pattern, the location, and the degree of fracture displacement. Nerve injuries range from a neuropraxic injury, due to nerve contusion or a shearing injury, to transection of the nerve roots. The S2 to S5 nerve roots control bladder, rectal, and sexual function; however, they do

not supply motor or sensory transmission to the lower leg. Continence and sexual function require at least unilateral preservation of the S2 and S3 nerve roots (Robles 2009).

Patients that sustain sacral fractures require careful clinical examinations to determine lower extremity sensory and motor functions and to identify injuries of the lower sacral plexus. A rectal examination is performed to evaluate rectal tone, sphincter contraction, and the bulbocavernosus reflex, and to exclude rectal injury as a potential sign of an open pelvic fracture.

2.8.2. Urologic injuries

Different types of pelvic ring disruptions might be associated with injuries to the lower urinary tract. However, the incidence of bladder and urethral injuries were 4% and 2%, respectively, in a recently published study based on National Trauma Data Bank information on 1400 pelvic fractures (Bjurlin et al. 2009). In earlier studies, the incidences were higher (Trunkey et al. 1974). Urethral injury occurred in both male and female patients, but the incidence was twice as high in males than in females (Bjurlin et al. 2009).

Bladder injuries

The emergency treatment for extraperitoneal bladder rupture is non-surgical catheter drainage. Surgical indications include bladder neck involvement, bone fragments in the bladder, and entrapment of the bladder wall within a ramus fracture line (Gomez et al. 2004, Lynch et al. 2005). Regardless of whether surgical treatment is indicated for the anterior pelvic ring injury, bladder reconstruction and internal fixation of a pubic ramus fracture or a disrupted SP can be performed simultaneously, within the first few days. Intraperitoneal bladder ruptures are treated surgically, due to the high risk of peritonitis. Bladder injuries have no acute influence on mortality.

Urethral injuries

The urethra, particularly the junction between the membranous and bulbar urethra, is vulnerable to injury, due to its proximity to the pubic rami and the puboprostatic ligaments (Flint and Cryer 2010). Partial posterior urethral tears can be treated non-surgically with catheter drainage (suprapubic or urethral catheter). Posterior urethral injuries can be managed acutely by realigning the urethra over a urethral catheter or with a suprapubic catheter for bladder drainage only, or by late repair. When the delayed approach is chosen, several months are required to allow the fibrotic stricture to stabilize before posterior urethroplasty can be performed. The delayed single-stage perineal urethroplasty provides good results, and a patent urethra can be re-established in the majority of men (Chapple et al. 2004, Myers et al. 2009). However, a recent study showed that the average time to spontaneous voiding was significantly shorter (35 days vs. 229 days), and stricture formation occurred significantly less frequently (14% vs. 100%) in patients that underwent early endoscopic repair compared to patients that underwent delayed repair (Hadjizacharia et al. 2008). In addition, Mouraviev et al. (2005) showed that early realignment of a disrupted urethra in men and early definitive repair of an injured urethra in women were both associated with improved long-term sexual

function. Urethral injuries have no acute influence on mortality, and they are not associated with emergency reconstructive indications.

2.8.3. Degloving soft tissue injuries

Directly applied forces may cause both crush and shear injuries to peripelvic soft tissues (Kottmeier et al. 1996). Degloving is defined as the detachment of skin and subcutaneous tissues from underlying fascia, which results in a disruption of segmental perforating vessels (Slack 1952). Closed soft tissue lesions, where the skin surface remains intact, are often overlooked or under-appreciated. In the mid-19th century, Morel-Lavallée first described this type of lesion as a traumatic detachment of skin from underlying fascia, which created a space filled with blood and necrotic fat (Kottmeier et al. 1996). Later, the injury may result in lymphocele formation. Since that original description by Morel-Lavellée, the eponym has been used to describe similar lesions in other anatomical regions.

The treatment for closed degloving lesions remains controversial. Morel-Lavallée soft tissue injuries can be treated with a minimally invasive technique that includes percutaneous drainage, debridement within three days after the injury, and a Hemovac drain (which is removed when drainage falls below 30 mL/24 hours) (Tseng and Tornetta 2006). Alternatively, these injuries can be treated with a more radical surgical technique that includes an incision over the whole length of the lesion, debridement, extensive irrigation, tending sutures, and wound drainage (Steiner et al. 2008). Open degloving injuries are treated with urgent, thorough debridement and wound irrigation, wound closure over drains, or use of negative pressure wound therapy (NPWT) (Collinge and Tornetta 2004). Decisions on the optimal timing, methods of definitive fracture fixation and soft tissue coverage are best made in conjunction with an orthopaedic trauma surgeon and a plastic surgeon experienced in soft tissue injuries associated with pelvic disruptions.

The Morel-Lavallée lesions have no acute influence on mortality. The healing rate is high, when treated with drainage, debridement, irrigation, and adequate wound management (closed or open). However, these lesions may influence morbidity and the long-term outcome.

2.9. Non-operative treatment of pelvic ring injuries

After the original description of a fracture-dislocation of the hemipelvis by Malgaigne in the 19th century, non-operative treatment methods have been described. These treatments involve combinations of bed rest, skeletal traction, closed reduction, a pelvic sling, and hip spica cast immobilization (Holdsworth 1948, Peltier 1955, Slätis and Huittinen 1972, Semba et al. 1983). None of these treatments permit early mobilization of the patient. In the presence of prolonged bed rest, a high incidence of serious pulmonary, urinary, and psychological problems have been documented (Trunkey et al. 1974).

Slätis and Huittinen (1972) performed late follow-ups for 65 of 163 Malgaigne fracture dislocations. They noted a 46% incidence of late sequelae, including oblique inclination of the pelvis upon

sitting, a pelvic limp, disabling sacro-iliac pain, signs of persistent damage to the lumbosacral plexus, and lower back pain. The non-operative modalities of treatment for unstable pelvic injuries have also been associated with serious chronic disabilities, such as a significant leg length discrepancy, severe lower back problems, markedly displaced non-unions, and in women, obstetric problems (Langloh et al. 1972, Trunkey et al. 1974, Henderson 1989).

Räf (1966) followed up 65 patients with double vertical pelvic fractures (type C injury) treated with non-operative methods. They found a more favourable outcome in cases where the posterior pelvic ring injury passed through the posterior ilium. When the posterior injury ran through the SI-joint, a large proportion of patients had persistent back pain. Patients with sacral fractures often had persistent nerve injury in the leg (sacral plexus injury) and genitourinary disturbances.

After non-operative treatment methods, approximately 40–60% of patients with pelvic fractures reported persistent pain, and only half of these patients reached their previous working level (Tile 1980, Henderson 1989, Fell et al. 1995, Tile 1995, Pohlemann et al. 1996b). Many of these late complications were attributable to inadequate reduction of the hemipelvis dislocation (Bucholz 1981).

2.10. External fixation for definitive treatment of pelvic ring injuries

In the late 1970s, anterior external fixation devices became popular for treating unstable pelvic fractures. Patients definitively treated with anterior external fixation frames showed better early results compared to patients that received conservative treatment (Carabalona et al. 1973, Slätis and Karaharju 1975, Gunterberg et al. 1978, Slätis and Karaharju 1980, Lansinger et al. 1984). The use of a trapezoid compression frame markedly diminished the severity of fracture pain, due to stabilization of the fracture fragments (Karaharju and Slätis 1979, Slätis and Karaharju 1980).

An anterior external fixation frame can restore pelvic bony stability in some, but not all, pelvic fracture types (Kellam et al. 1989). It has been well established that an anterior external frame is beneficial for treating AP compression pelvic ring instability (type B open book injuries) (Gilliland et al. 1982). However, this approach cannot produce sufficient posterior compression across the sacroiliac joint for adequate stabilization of the posterior pelvis. Moreover, later biomechanical and clinical studies showed that anterior external frames did not restore sufficient stability to an unstable type C disruption of the pelvic ring; treated patients could not ambulate without risking re-displacement of the fracture, even when no weight was carried on the affected side (Mears and Fu 1980, Wild et al. 1982, Kellam 1989, Tile 1995).

The advantage of an external fixator is that it is easy to apply. External fixators can be used when internal fixation is hazardous for injuries of the anterior pelvic ring, due to potential contamination from rectal or abdominal injuries. External fixation devices are also easy to remove. A disadvantage is that, because they are external devices, they can interfere with sitting and mobilization. Pin sites

require care, and pin site infections are typical. Additionally, it is difficult to obtain and maintain an anatomical reduction of anterior and posterior pelvic ring injuries with an anterior frame.

The various anterior external fixation frames are relatively similar in stability. Ponsen et al. (2003) compared the stiffness of several current anterior external fixation systems with that of an aluminium replica of the human pelvis with a type C injury. They found that all the tested external fixators provided low stability. However, the single bar systems were stiffer and performed better than frame configurations. The difference in performance was attributed to the use of 6-mm pins instead of 5-mm pins; i.e., two 6-mm pins provided 15% more stiffness than three 5-mm pins, and to the fact that the single bar systems employed stiffer bars than the more slender rods used in the frames. Other factors were not significant, including the placement of the pins in a cranial (iliac crest) or ventral (AIIS) location.

2.11. Operative treatment of pelvic ring injuries

Prior to the 1980s, operative treatments for pelvic fractures were the exception to the rule. In 1913, Albin Lambotte (1866-1955), the father of modern osteosynthesis, published a book that described different operative techniques for pelvic stabilization. These techniques included cerclage wiring of the symphysis pubis, sacral bar osteosynthesis, iliosacral screw fixation, and retrograde screw fixation of pubic rami fractures (Rommens and Tile 2003). After recognizing the correlation between late deformities, instabilities, and severe pain, the common opinion gradually changed. Currently, a century after the work of Lambotte, internal fixation is the preferred treatment for unstable pelvic ring disruptions.

In type C pelvic injuries, the anterior and posterior parts of the pelvic ring are disrupted, which leads to vertical translational and rotational instability. The goals of treatment are realignment, restoration of pelvic ring stability, and decompression of the sacral plexus nerve roots, when indicated. Biomechanical studies have shown that, in type C injuries, the best stability can be achieved by internal fixation of the posterior and anterior pelvic ring injuries (Leighton et al. 1991, Tile 1995). Thus, methods of open reduction and internal fixation (ORIF) were introduced (Goldstein et al. 1986, Kellam et al. 1987, Ward et al. 1987, Tile 1988, Matta and Saucedo 1989, Hirvensalo et al. 1993, Pohleman et al. 1994). More recently, closed reduction and percutaneous screw fixation techniques have been developed (Ebraheim et al. 1987, Routt et al. 1995, Routt and Simonian 1996a).

Various methods for pelvic fracture stabilization have been described. Internal fixation has become the preferred treatment for unstable posterior pelvic ring injuries (Kellam et al. 1987, Matta and Saucedo 1989, Pohlemann et al. 1996, Tornetta and Matta 1996); however, indications for fixation of anterior pelvic ring injuries have been a controversial issue (Hirvensalo et al. 1993, Routt et al. 1995, Matta 1996, Routt and Simonian 1996b). Many studies have focused on emergency management and initial treatment, but there is a lack of adequate follow-up studies on pelvic ring injuries.

2.12. Internal fixation techniques

Posterior pelvic ring disruptions are difficult to stabilize rigidly, and there is no clinical consensus on the optimal fixation technique for these injuries (van Zwienen et al. 2005, Papakostidis et al. 2009, Suzuki et al. 2009b). Similarly, numerous methods have been described for stabilizing anterior pelvic ring injuries (Matta and Saucedo 1989, Hirvensalo et al. 1993, Simonian et al. 1996b, Grimshaw et al. 2012), but there is no clear consensus of the indications for internal fixation.

2.12.1. Sacral fractures (61-C1.3)

Among all pelvic ring disruptions, sacral fractures are the most difficult to reduce and stabilize (Tile 1995, Tornetta and Matta 1996). Biomechanical studies have demonstrated different degrees of stiffness in fixation constructs for sacral fractures (Gorczyca et al. 1996, Simonian et al. 1996a, van Zwienen et al. 2005). After an anatomical reduction, several different types of fixation techniques are available for vertically unstable sacral fractures, including iliosacral screws, ilio-iliacal techniques (sacral bars, transiliac plates), local small sacral plates, and spinal instruments.

Iliosacral screw fixation

Iliosacral screw fixation is the gold standard for the fixation of vertically unstable sacral fractures (Matta and Saucedo 1989, Matta and Tornetta 1996). Severely displaced sacral fractures are typically approached posteriorly, with the patient in the prone position, through a vertical incision. The sacral fracture is observed and reduced with forceps. After achieving reduction, the sacral fracture is fixed with one or two iliosacral screws. Minimally displaced sacral fractures might be amenable to a closed reduction with percutaneous iliosacral-screw fixation, with the patient either in a prone or supine position, depending on the fracture pattern of the whole pelvic ring and concomitant injuries (Routt et al. 1995, Routt and Simonian 1996a).

Various imaging techniques have been used to facilitate proper iliosacral-screw fixation, including fluoroscopy (Matta and Saucedo 1989), CT (Ebraheim et al. 1994, Goldberg et al. 1998), fluoroscopic CT, and computer-assisted techniques (Tonetti et al. 1998, Gautier et al. 2001). Conventional fluoroscopy is the current standard for intraoperative imaging (Matta and Saucedo 1989, Keating et al.1999, van den Bosch et al. 2002). It is crucial to determine the correct entry point and the correct angle in all planes for placing the iliosacral-screw to avoid perforating the sacrum or sacral foramina. An image intensifier can only visualize one plane at a time; therefore, it is necessary to examine anteroposterior, inlet, and outlet views, and lateral sacral images. Problems in proper screw placement are associated with difficulties in imaging and anatomical variations in the sacroiliac complex.

Van Zwienen et al. (2005) found no difference in stiffness when the technique was performed with one or two iliosacral-screws. However, compared to fixation with one screw, when two iliosacral-screws were used, a significantly higher load and significantly more loading cycles were required to cause failure. That cadaveric study also demonstrated that both translational and rotational stiffness were superior in the intact pelvis compared to the fixed pelvis. The screws should be placed at least

past the midline of the sacrum. Fully threaded cannulated screws are used in comminuted and trans-foraminal sacral fracture fixations to avoid compression of the sacral neural foramina (Simonian et al. 1996a).

Three dimensional computer-assisted navigation facilitates screw placement with less radiation and a similar operation time, compared to the conventional fluoroscopy-guided procedure (Zwingmann et al. 2009). A three-dimensional image intensifier can also be used intraoperatively to control the quality of reduction and to guide correct placement of the iliosacral-screws. Recently, a method was introduced for creating realistic SI-corridor models and computing optimal screw trajectories in an automated PC-based platform (Mendel et al. 2013).

Ilio-iliacal techniques

There are four main ilio-iliacal techniques for sacral fracture fixation: extraosseous transiliac bars (sacral bars) (Shaw et al. 1985, Ebraheim et al. 1991), intraosseous sacral bars (Vanderschot et al. 2001, Mehling et al. 2012), transiliac plates (a posterior tension band plate) (Krappinger et al. 2007, Suzuki et al. 2009b, Hao et al. 2009), and an ilio-iliacal internal fixator (Dienstknecht et al. 2011). Fot the transiliac plate fixation technique, the pre-bent 4.5-mm reconstruction plate (Krappinger et al. 2007) or locking compression plate (Hao et al. 2009) might be secured at or below the level of the PSIS. The screws are inserted into the iliac wings without penetrating the SI-joint. In a recent study, a minimally invasive, adjustable ilio-iliacal plate was introduced for stabilizing sacral fractures and other posterior pelvic injuries (Chen et al. 2013). This implant can be used without pre-bending, and it is secured with screws inserted into both the iliac wing and the sacrum.

No study is available for the long-term outcome of a sacral bar stabilization. In a series of 23 patients with type C injuries treated with the percutaneous transiliac plate osteosynthesis technique, the clinical outcome (POS) was graded excellent or good in 73.9% of patients (Krappinger et al. 2007). Loss of reduction occurred in 8.7% of patients. A good bony reconstruction showed a trend in better clinical results. Lumbosacral plexus lesions and permanent urogenital complaints were associated with worse clinical results. In a recent study that included 18 patients with comminuted sacral fractures treated with the ilio-iliacal plate fixation, functional outcome (Majeed Score) was excellent or good in 72.2% of patients (Suzuki et al. 2009b). Two patients (11.1%) showed slight losses of reduction. A persistent neurological deficit led to significantly lower functional scores.

Ilio-iliacal techniques have some disadvantages, including limited reduction possibilities, bilateral bridging of the SI-joint in the unilateral injury pattern, difficulty in precontouring the plate, and a higher rate of symptomatic implants (Krappinger et al. 2007, Suzuki et al. 2009b).

Direct plate fixation

A sacral fracture fixation with small fragment implants (small sacral plates) has been introduced as an alternative approach (Pohlemann et al. 1994, Gänsslen et al. 2003). Gänsslen et al. (2003) performed a study on 32 patients with sacral fractures treated with open reduction and sacral plating. They achieved anatomical or near-anatomical (<5 mm) reconstruction in 96% of cases. In the same

study, secondary displacement occurred in 6.3% of cases. The over-all complication rate was 21.9%. This direct plating technique might be useful in sacral fractures lateral to the sacral foramina (Denis zone I). However, in transforaminal sacral fractures (zone II), short local plates cannot be used without screw penetration into the sacral canal; therefore, these fractures require longer transverse plates that pass over the midline.

2.12.2. SI-joint injuries (61-C1.2) and transiliac fractures (61-C1.1)

In a cadaver dissection study on patients that died of trauma injuries, type C injuries with complete disruption of the SI-joint (C1.2) were associated with a triplane displacement of the hemipelvis (Bucholz 1981). The displacement was typically cranial, posterior, and externally rotated. They found that a closed reduction with traction and external pelvis manipulation was not possible, because the osseous and ligamentous tissues interposed into the joint. Stability of the SI-joint is based on accurate reduction, but also on sacroiliac geometries that may limit manipulations, such as the concave-convex shape of the opposing joint surfaces in every plane, and the small anterior shelf of bone on the ilium (Dommisse 1960, Shaw et al. 1985).

Operative treatments for SI-joint dislocations and fracture dislocations can be performed with an anterior approach, with the patient in a supine position (Simpson et al. 1987), or with a posterior approach, with the patient in a prone position (Tile 1995). Open reduction of the SI-joint with a posterior approach is difficult, because it is possible to control reduction with mere finger palpation through the sciatic notch. Therefore, in most cases, an anterior approach is selected. It allows simultaneous reduction and fixation of the SI-joint, SP, and pubic rami fractures, with the patient in the supine position. In a biomechanical cadaveric study, there was no statistically significant difference between fixations of SI-joint disruptions that were performed either with an anterior SI-joint plate (four-holed plate) or with three iliosacral-screws (Leighton et al. 1991).

Transiliac fractures (C1.1) cannot be stabilized with an external fixator. Open reduction is performed with the same anterior approach along the iliac crest as that used in SI-joint disruptions. Fixation of iliac wing fractures is achieved with 3.5-mm reconstruction plates or long, 3.5-mm cortical screws, with interfragmental compression.

2.12.3. Anterior pelvic ring injuries

Biomechanical comparisons of techniques for stabilizing anterior pelvic ring injuries focus on symphysis pubis disruptions. The internal fixation of the SP is more stable than an external fixation for both type B open book injuries and vertically unstable type C fractures (Leighton et al. 1991, Tile 1995). Numerous methods of internal fixation have been described for stabilizing the symphysis. Two plates, one superior and one anterior, provide better strength than a single plate (Tile et al. 2015). Box plates (Simonian et al. 1996b) and locked plates (Grimshaw et al. 2012) have not demonstrated additional benefit in stabilizing the symphysis.

The anterior injury may also consist of uni- or bilateral pubic rami fractures or combinations of rami fractures and a symphyseal disruption. Initially, internal fixation of the anterior and posterior aspects of the pelvic ring included plating the symphysis and stabilizing the sacroiliac complex with screws or plates (Goldstein et al. 1986, Kellam at al. 1987, Ward et al. 1987, Matta and Saucedo 1989). Any rami fractures were considered to be less important and were only sporadically stabilized with internal fixation. However, it has been shown that stabilization of the whole anterior arch is important for the overall stiffness of the pelvic ring.

2.12.4. Spinopelvic dissociation

In H-shaped sacral fractures with spinopelvic dissociations, the transverse sacral fractures are angled, and they undergo translational displacement, or even complete fracture displacement. This condition results in gross spinopelvic instability and neurologic deficits in the cauda equina. Another common presentation is an injury to the L5 and S1 nerve roots associated with vertical sacral fracture lines. The L5 nerve root can be injured as a result of vertical shear displacement of the sacrum, which is often accompanied by a fracture in the transverse process of L5. A S1 nerve root injury is associated with transforaminal (zone II) sacral fractures (Denis et al. 1988).

Treatment for a spinopelvic dissociation has evolved from a non-operative approach to open reduction and segmental lumbopelvic fixation (Roy-Camille et al. 1985, Schildhauer et al. 2006). Roy-Camille et al. (1985) presented three different types of fixation techniques for spinopelvic dissociations, including lumboiliac plates, lumbosacral plates, and Harrington rods connected to a transverse bi-iliac bar. In all these techniques, proximal stability was achieved at the L4 and L5 laminae or pedicles, and distal stability was achieved at the upper central segment of the sacrum or the iliac wings.

The goals of treatment are realignment, restoration of spinopelvic stability, and decompression of the nerve roots, indirectly and/or directly. Allen and Ferguson (1984) were the first to report on their experience with the Galveston technique, where the distal fixation points are located on the posterior part of the iliac wings, above the sciatic notch, and between the laminas. Recently, studies have been published on the use of segmental lumbopelvic fixation in the management of spinopelvic dissociations (Schildhauer et al. 2006, Ayoub 2012, Tan et al. 2012).

In addition to H-shaped injuries, other possible sacral fracture patterns that occur with spinopelvic dissociations include the U-, Y-, and T-shaped sacral fractures (Robles 2009, Gripnau et al. 2009, Yi and Hak 2012). Of these, H-shaped sacral fractures are the most difficult to reduce and stabilize, due to the highly unstable caudal sacral segment. Decompressing a neural injury indirectly with fracture reduction and/or directly with a sacral laminectomy remains controversial. The indications for sacral laminectomy are variable, and no clinical consensus exists (Schildhauer et al. 2006, Ayoub 2012, Tan et al. 2012, Yi and Hak 2012). The question of whether the anterior pelvic ring injury requires internal fixation when lumbopelvic fixation is performed posteriorly remains to be discussed. Additionally, few factors have been identified that are associated with outcomes after operative treatment.

2.13. Outcome measurement instruments

In the past, evaluation of long-term results after pelvic ring disruptions have focused on radiological outcomes or nonvalidated measures of pain and function that did not facilitate comparison of results from one report to the next (Kreder 2003). With the development of outcome instruments, deficits in physical, social, and emotional function subsequent to injury can now be consistently quantified (Kreder et al. 1997). Several outcome measures are used to describe the results of treating pelvic ring injuries. Currently, the most commonly used validated scoring systems are the SF-36, the musculoskeletal function assessment (MFA), and the Oswestry low back pain disability questionnaire. In addition, there are non-validated systems, including the Majeed Score and the outcome instrument of the German multicentre study group pelvis (POS/GMS1 scale).

Short-form health survey (SF-36)

The medical outcomes study produced a 36-item short-form general health survey (SF-36) that is used for self-assessments of mental health, physical health, and social interactions (Ware et al. 2000). The SF-36 scores range from 0 to 100, with higher scores indicating a better state of health. Eight different scales are analysed, and they can be aggregated into two summaries; the physical component summary and the mental component summary. The component summaries have been shown to be valid (Ware and Gandek 1998). The SF-36 is a measurement instrument for evaluating the overall quality of life. A clear disadvantage is that, although relevant impairments in quality of life are captured, the relative importance of individual limitations is not sufficiently analysed (Gänsslen and Lindahl 2013).

Musculoskeletal function assessment (MFA)

The 101-item MFA is a validated self-reported health-status questionnaire designed to detect differences in the functional status of patients with a broad range of musculoskeletal disorders (Martin et al. 1996, Engelberg et al. 1999). Its short form (SMFA) is a two-part, 46-item, self-reported health-status questionnaire that can also be used for clinical evaluations of treatment impact on individual patients after an injury (Swiontkowski et al. 1999).

The main disadvantage of the SF-36 and MFA scores is that they only evaluate the difference in disability compared to a normal population. A separate, pelvis-related outcome cannot be measured with these instruments. They can only measure the percentage difference in disability compared to a normal population of the same age.

Oswestry low back pain disability questionnaire

The Oswestry low back pain disability questionnaire measures the patient's permanent functional disability in the lumbosacral region (Fairbank and Pynsent 2000). The questionnaire consists of 10 items, with each item rated on a scale of 0-10%. The items are: pain intensity, personal care (e.g., washing, dressing), lifting weight, walking ability, impairment while sitting, standing or sleeping, sexual impairments, social life, and ability to travel. Based on the total score, lower back pain is

classified into five categories of disability, as follows: minimal (0-20%), moderate (21-40%), severe (41-60%), crippled (61-80%), and bed bound or the patient has exaggerated the symptoms (more than 80%).

Majeed score

The Majeed score is a pelvic fracture-specific functional assessment instrument, which is based on clinical findings. The maximum score is 100 points for patients that were working before the injury or 80 points for patients that were not working before injury (Majeed 1989). The items are rated according to different scales, as follows: pain (30 points), sitting disturbances (10 points), sexual impairments (4 points), and walking ability (36 points). The latter item is subdivided into three categories: the use of walking aids (12 points), analysis of unaided gait (12 points), and the distance the patient is able to walk (12 points). The main disadvantage of this instrument is that neurological impairments are not integrated into the score, even though these impairments have relevant prognostic influence on outcome of patients with pelvic fractures and deficits in the lumbosacral plexus or cauda equina.

German multicentre study group pelvis outcome scale (POS)

The POS (GMS1 scale) is a non-validated scale that consists of three items: clinical results, radiographic results, and social reintegration (Pohlemann et al. 1996). The clinical results include pain, functional impairment (limping, walking assistance, wheel chair use), persistent neurological impairment, and bladder and bowel dysfunction. Radiological results focus on the reconstruction of the posterior pelvic ring and also on the integrity of the anterior pelvic ring. Social reintegration includes working ability, leisure activities, sporting activities, social activities, and need for external assistance. To estimate the total result of the pelvic ring injury, the radiological (3 points) and clinical results (4 points) are summarized as one score on a 7-point scale, where the maximum of 7 represents an excellent result, 6 represents a good result, 4 and 5 represent a fair result, and 2 and 3 represent a poor result.

2.14. Outcome after operative treatment of pelvic ring injuries

Many studies have focused on emergency management and initial treatment of unstable pelvic ring injuries, and they have described several techniques for treating these injuries. In contrast, there is a lack of adequate follow-up studies on pelvic ring injuries (Papakostidis et al. 2009). No clear data are available regarding outcome parameters and instruments for evaluating specific fracture types, stabilization procedures, or treatment concepts.

Conservative treatment of unstable type C pelvic injuries has produced unacceptable results. Approximately 40 to 60% of patients report persistent pain, and only 50% reach their previous working level (Tile 1980, Goldstein et al. 1986, Henderson 1989, Tile 1995). Therefore, during the last few decades, several studies have reported outcomes related to different types of internal fixation con-

cepts for treating type C pelvic ring injuries; however, type B injuries have generated only minor interest.

Concomitant injuries in other body regions and additional injuries in the pelvic region (complex pelvic trauma) seem to influence the overall results. A disadvantage of many studies is that no consistent treatment strategy was followed, and therefore, the outcome after treating a pelvic ring injury might be influenced by the treatment concept applied (Gänsslen and Lindahl 2013).

Comparative analyses of the outcomes in type B and C injuries have generated controversial results. Many reports have shown that the degree of instability in the pelvic ring influenced the long-term result; thus, type B injuries tend to have a better prognosis than type C injuries (Pohlemann et al. 1994, Dujardin et al. 1998). In a recent multicentre analysis, functional outcome decreased with increasing pelvic ring instability over the range of type A to type C injuries (Dźupa et al. 2011). Neurological long-term sequelae also increased with the severity of pelvic ring injury; after treatment, long-term neurological sequelae occurred in 4% of type A, 11% of type B, and 17% of type C injuries. However, when the SF-36 was used for evaluations, no difference was found among the three fracture groups (Oliver et al. 1996). In addition, type B open book injuries were associated with the greatest degree of disability, followed by type C injuries, and finally, type B lateral compression injuries were associated with the lowest degree of disability (Kreder 2003).

2.15. Organization of pelvic trauma care in Finland

Frequently, orthopaedic injuries are a determining factor for ultimate disability and quality of life for a patient that sustained a trauma. To promote optimal care and better outcomes, it is important to establish a designated orthopaedic trauma system and regionalization. Finland is a relatively small country with 5.4 million inhabitants. The public health care system is hierarchical, based on 54 community hospitals (primary hospitals), 16 central hospitals (secondary hospitals), and five university hospitals (tertiary hospitals) with the largest responsibilities (Handolin et al. 2006).

The treatment of unstable pelvic ring fractures is a major challenge, even without vascular or neurological compromise, as these fractures are rare, and thus, the case load is small at primary and secondary hospitals. Therefore, the definitive treatment of unstable pelvic ring and acetabular fractures has been centralized to five university trauma hospitals in Finland. Only uncomplicated fractures might be treated at some central hospitals. This centralization has improved the level of care and optimized the cost-benefit of trauma care by increasing the case load and re-allocating resources (Handolin et al. 2006).

3.   AIMS OF THE PRESENT STUDY

The purpose of this study was to evaluate the results of emergency treatment of pelvic fractures with arterial hemorrhage. The use of an anterior external fixator was assessed for acute treatment, and as a definitive treatment of type B and C pelvic ring disruptions. The radiological and clinical outcomes were examined after surgical management of unstable type C pelvic ring injuries and H-shaped sacral fractures with spinopelvic dissociation.

The specific aims of the study were:

1.   To assess the long-term radiological and functional results of type B and C pelvic ring injuries that were treated with a trapezoid compression external fixator as a definitive treatment.

2.   To evaluate the findings and outcome of pelvic fracture-related massive retroperitoneal arterial hemorrhage treated with early (within 24 hours) angiographic embolization, and to identify early prognostic emergent parameters that indicate a predisposition to treatment failure and patient death (30-day mortality).

3.   To evaluate the long-term radiological and functional outcomes of rotationally and vertically unstable type C pelvic ring injuries treated with a standard reduction and internal fixation of the posterior and anterior parts of the pelvic ring.

4.   To evaluate the radiological and clinical outcomes, including neurological recovery, after segmental lumbopelvic fixation and neural decompression of H-shaped sacral fractures with spinopelvic dissociation, and to identify prognostic factors that predispose to the final outcome.

4. PATIENTS AND METHODS

Patients were treated at the Töölö Hospital, the level I trauma centre of Helsinki University Hospital. The study protocols were approved by the institutional review board (**I-IV**) and local ethics committee (**I, III-IV**). Principles of the Declaration of Helsinki were obeyed in all studies.

An anterior trapezoid compression external fixator was used as a definitive treatmet for type B and C pelvic ring injuries since the late 1970s until the early 1990s. After that, the treatment protocol in type C pelvic injuries has been to restore the anatomy of the pelvic ring with standardized reduction and internal fixation techniques of the posterior and anterior parts of the pelvic ring.

4.1. Identification of study populations

Patients with unstable pelvic ring injuries were identified from the operating room register and by querying the hospital surgical procedure database for diagnosis codes (ICD-9, ICD-10) for pelvic ring fracture (S32.7), sacral fracture (S32.1), iliac wing fracture (S32.3), and disruption of the SP (S32.5), and for procedure codes (NOMESCO) for external fixation (NEJ70) and for internal fixation (NEJ50, NEJ86) from 1982 through 2011.

Study I consisted of patients with type B and C pelvic ring injuries who were treated with an external compression skeletal fixator as a definitive treatment between January 1982 and December 1993.

In **Study II**, patients with pelvic fracture-related arterial bleeding, diagnosed and controlled with TAE, were collected prospectively since May 1996, when this treatment method was started as part of early control of massive arterial pelvic bleeding at our institution, until December 2008.

Study III consisted of patients with type C pelvic ring injuries who were treated with standardized operative techniques from May 1989 through May 2000**.**

In **Study IV**, H-shaped sacral fractures with spinopelvic dissociation were collected prospectively and also by reviewing the hospital records since 1993, when the first lumbopelvic fixation procedure was performed at our institution, through July 2011.

An overview of timeframes and patient populations of the studies is presented in **Table 3**. Geographical catchment area of the Töölö Hospital has remained the same throughout the long study period, but the population has increased from 1.5 to 1.8 million inhabitants.
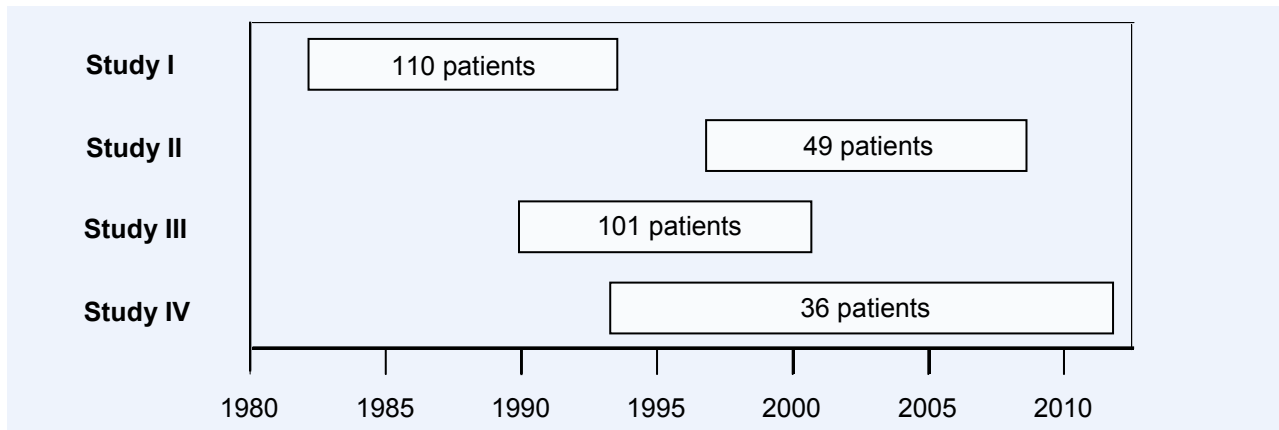
4.2. Study design

Study I was a follow-up study of 132 consecutive patients with type B and C unstable injuries of the pelvic ring who were treated with closed reduction and external fixation as a definitive treat-

ment during a 12-year period. Of these patients, 110 were available for physical, functional and radiological late follow-up examination; 16 had died and 6 had been lost to follow-up (**Table 3**).

Study II was a retrospective cohort study of patients sustaining pelvic fracture-related arterial bleeding, diagnosed and controlled with TAE within the first 24 hours during a 12-year period. The study population consisted of 49 consecutive patients including the first patient treated with TAE at our trauma center in 1996. No patients were lost to follow-up.

Table 3. Patient populations and time frames of Studies I-IV.

Study I	110 patients			
Study II			49 patients	
Study III		101 patients		
Study IV			36 patients	
	1980 1985 1990 1995 2000 2005 2010			

Study III was a follow-up study of all patients with type C pelvic ring injuries treated within 21 days of injury with standardized closed or open reduction and internal fixation techniques during an 11-year period (117 patients). Spinopelvic dissociations were excluded from this analysis since they form a specific type of pelvic injury. Four patients with paraplegia associated with an unstable thoracolumbar fracture or rupture of the abdominal aortae were excluded, *7* died (three within 30 days because of MOF and 4 later), and *5* patients were lost to follow-up leaving 101 patients to form the study population.

Indications for operative treatment. In **Study III**, completely unstable posterior pelvic ring injuries with fracture of the sacrum, dislocation or fracture dislocation of the SI-joint, or transiliac fracture, were regarded as indications for open or closed reduction and internal fixation. In addition displaced (>10 mm) uni- or bilateral fractures of the pubic rami or disruption of the SP or different combined injuries of these were also indications for internal fixation. A concomitant acetabular fracture with displacement of more than 2 mm in the weight bearing surface was an indication for ORIF (14 fractures in 12 patients in Study III).

Study IV was a follow-up study of all H-shaped sacral fractures with spinopelvic dissociation who were operated using segmental lumbopelvic fixation. In an 18-year study period, 37 patients fulfilled the inclusion criteria. One patient died six weeks after the initial trauma from head injury and was excluded from the analysis. This gave a total of 36 patients entered for analysis.

Patient demographics, ISS, mean follow-up times, and injury mechanisms are presented in **Tables 4 and 5** (**Studies I-IV**). The pelvic ring fractures were classified according to Tile (1995) and the

acetabulum fractures according to Judet et al. (1964). The associated injuries were classified using the Injury Severity Score, ISS, and the New Injury Severity Score, NISS. The Abbreviated Injury Scale (AIS) 2005 version was used for ISS and NISS assessment.

Table 4. Patient demographics and mean follow-up times in Studies I-IV.

	Study I (n=110)	Study II (n=49)	Study III (n=101)	Study IV (n=36)
Gender (F/M)	62 / 48	20 / 29	35 / 66	18 / 18
Mean age (range)	39 (13-87) yrs	43 (16-92) yrs	33 (15-79) yrs	34 (15-66) yrs
ISS	25 (10-57)	37 (10-66)	29 (10-57)	27 (16-54)
Open fractures	4 (4%)	5 (10%)	4 (4%)	4 (11%)
Mean follow-up time	4.1 (1-11) yrs	30 days [a]	1.9 (1-7) yrs	2.8 (1.5-5.9) yrs

[a] minimum (30-day mortality)

Table 5. Mechanism of injury in Studies I-IV.

Injury mechamism	Study I (n=110)	Study II (n=49)	Study III (n=101)	Study IV (n=36)
Traffic accident	68 (62%)	24 (49%)	42 (42%)	6 (17%)
Fall from a height	31 (28%)	20 (41%)	46 (45%)	27 [a] (75%)
Crush injury	7 (6%)	2 (4%)	12 (12%)	3 (8%)
Miscellaneous	4 (4%)	3 (6%)	1 (1%)	0 (0%)

[a] The fall was intentional (suicide attempts) in 18 patients

In **Study II** data collection included vital signs, physiological and laboratory parameters, the presence of retroperitoneal hematoma or contrast blush in trauma CT in the pelvis, bleeding vessel sites and sizes in angiography (O'Neill et al.1996), 30-day mortality, cause of death assessed by medico-legal autopsy, and TAE-associated complications. Vital signs were defined as systolic blood pressure (SBP), heart rate (HR), respiratory rate (RR), and Glasgow Coma Scale (GCS) (Teasdale and Jennett 1974); and laboratory tests as hemoglobin concentration (Hb), pH, base excess (BE), thromboplastin time (TT), trombosytes (tromb), and platelets (plat). Both the first and the worst vital signs and laboratory tests at the emergency room were recorded. Fluid resuscitation and blood product replacements were recorded.

In **Study IV** the transverse fracture component of the H-shaped sacral fracture was classified according to Roy-Camille et al. (1985). In addition, the Roy-Camille type 2 and 3 transverse sacral fractures were subclassified as partially displaced (type 2a and 3a) and as completely displaced fractures when the translational displacement in AP direction in sagittal views was more than the thickness of the sacrum (type 2b and 3b) (**Fig. 3**).
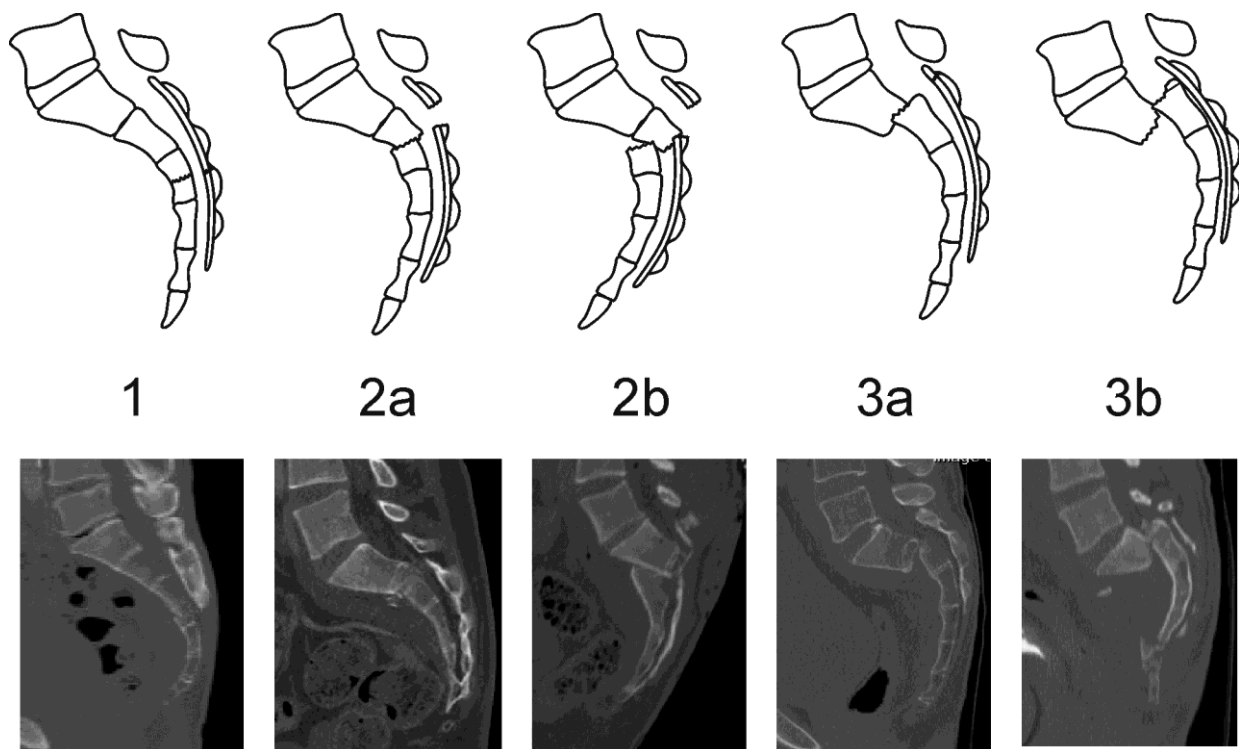
Figure 3. A modified Roy-Camille classification for transverse sacral fractures with spinopelvic dissociation.

4.3. External fixation of pelvic ring injuries

In **Study I,** a trapezoid compression external fixator was used as described by Slätis and Karaharju (1975, 1980). Three 6-mm pins on both sides were inserted into the iliac crest percutaneously or through small incisions. The inclination of the iliac wing was ascertained by guide-pins applied along the inner and outer aspects of the iliac wing while inserting the pins into the bone. The first pin was inserted 2 cm from the ASIS in the center of the iliac crest so that the pin advanced in the interspace between the outer and inner laminas. Correct positioning was sensed as a constant resistance. The second and third pins were inserted through the guide block parallel on a straight line along the crest. Next the bilateral vertical bars and the upper horizontal bar were connected to the pins with clamps. Finally, the lower horizontal compression bar was mounted and compression was applied (**Fig.4**).

Closed reduction of the displaced hemipelvis in type C injury was achieved by simultaneous manual distraction of the lower extremity and bilateral compression at the level of the trochanters before final tightening of the horizontal bars. In open book injuries the diastasis of symphysis pubis was most frequently reduced by manual compression utilizing the attached frame components. Reduction was also possible to achieve by rolling the patient into the lateral decubitus position.

For type C injuries, mobilisation with crutches was started after six weeks bed rest and the full weight bearing was allowed after 10 to 12 weeks (**Study I**). For type B injuries, mobilization was started during the first week if associated injuries allowed.
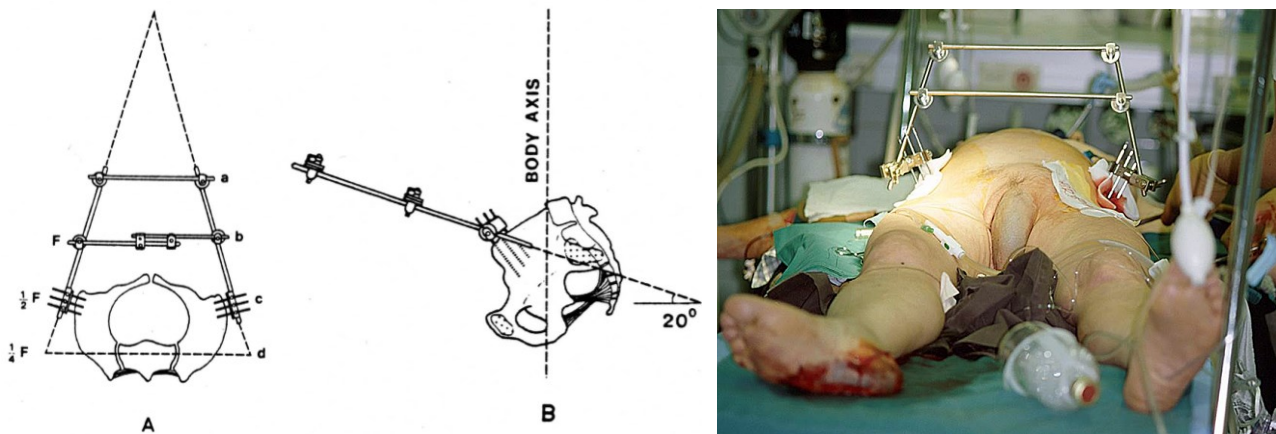
Figure 4. Trapezoid compression external frame (Slätis and Karaharju).

4.4. Transcatheter angiographic embolization (TAE)

Traumaresuscitation

Primary resuscitation of all hemodynamically unstable patients with pelvic fractures were carried out according to the ABCDE principles. Fluid resuscitation was started with crystalloids and continued with blood component therapy. There were no major changes in the fluid resuscitation strategy during the study period, since hemostatic fluid resuscitation therapy (1:1:1) was introduced in our institute only later on. Chest X-ray, FAST, and pelvic X-ray were obtained on admission. Trauma-CT was performed for patients assessed to be hemodynamically stable enough. However, in cases of massive bleeding, emergency procedures for bleeding control were carried out before trauma-CT.

Emergency bleeding control procedures

An anterior external fixator or pelvic binder was used as an emergency treatment in pelvic fractures associated with an increase in pelvic volume and/or severe vertical instability **(Study II)**. In cases with major free abdominal fluid, laparotomy was carried out first. The indication for TAE was a pelvic ring and/or acetabular fracture in plain pelvic X-ray in hemodynamically unstable patient without intra-abdominal fluid in FAST or CT, and the pelvis was considered the main source of bleeding. TAE was also indicated if laparotomy revealed major (expanding) retroperitoneal hematoma. Pelvic packing was used exceptionally during laparotomy to control retroperitoneal arterial pelvic bleeding through a ruptured peritoneum.

TAE technique

Embolization procedure was started with diagnostic angiography performed through the femoral artery with 5F catheters and this consisted of aortal, bilateral common iliac artery and internal iliac artery injections. When the actively bleeding artery was found, a 3F microcatheter (Tracker-18, Target Therapeutics, Fremont, California) with a guidewire was introduced via the angiographic catheter close to the bleeding point and embolization was performed with glue (mixture of n-bytyl-

cyanoacrylate and iophendylate, at a ratio of 1:1) or fibered platinum microcoils (Target Therapeutics). If there were many bleeding sites distal to the internal iliac trunk, each was embolized separately (selective embolization) in patients stable enough. If the patient was in extremis and several bleeding points were found, then proximal non-selective embolization of the internal iliac artery was carried out (**Fig. 5**). The embolization procedure was stopped when the control angiogram showed no bleeding.
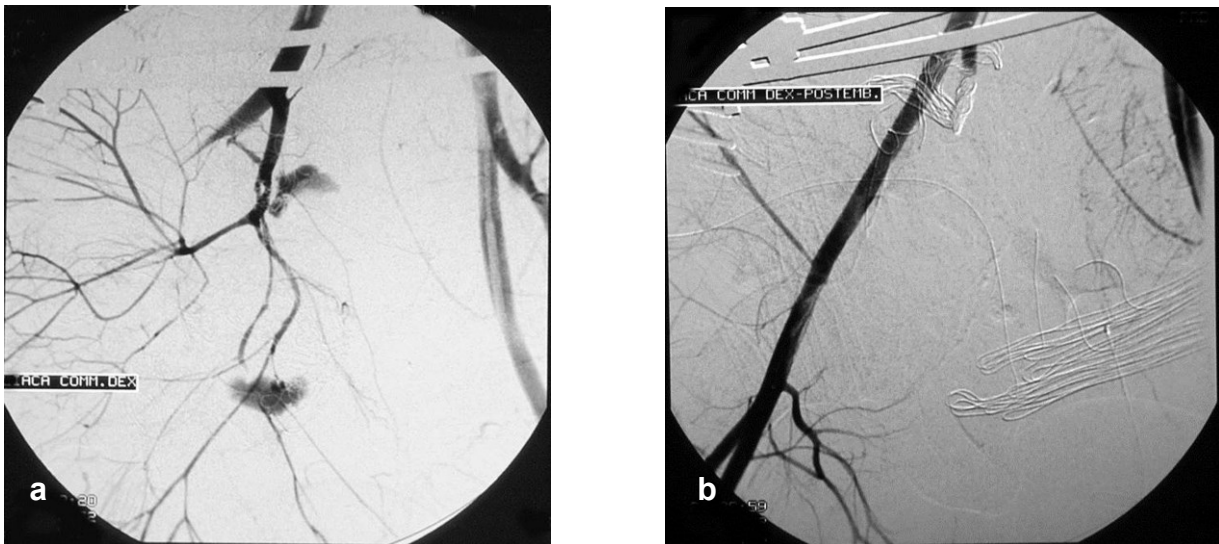

Figure 5. Angiography of the internal iliac artery before and after embolization (non-selective embolization). (a) Initial angiogram shows several bleeding vessels; (b) the control angiogram shows no bleeding.

Angiographic assessment

The angiographic findings were graded as either isolated or multiple, uni- or bilateral arterial disruptions. Classification of the bleeding vessel size and vessel score was performed according to O'Neill et al. (1996), with the vessel score being the sum of the scores of each bleeding vessel. The connection of the bleeding arteries with the fracture type and site were analyzed. Special attention was paid to the effectiveness of embolization (successful bleeding control) and re-bleeding (failure to achieve bleeding control).

4.5. Internal fixation of posterior pelvic ring injuries

The posterior part of the pelvic ring was most commonly operated first if the displacement in the anterior pelvic ring injury was minimal. However, major initial displacement in the SP (diastases and/or translation) or in the rami fracture site (> 10 mm) indicated first correction of the anterior deformity following reduction and fixation of the posterior injury **(Study III)**. In type C1.1 or C1.2 injuries, a simultaneous ORIF through two anterior approaches, one along the iliac crest and one through the low midline incision (Hirvensalo et al. 1993), was chosen. Bladder injury was not considered a contraindication for simultaneous ORIF of the anterior pelvic ring injury.

Sacral fractures (61-C1.3)

Displaced sacral fractures with neurologic compromise were reduced and stabilized with the patient in the prone position with one or two cannulated iliosacral screws across the fracture line into the S1 vertebral body under fluoroscopic guidance (Matta and Saucedo 1989). Partially threaded cannulated 7.0-7.3-mm screws were used in simple sacral fractures and fully threaded screws in comminuted sacral fractures to avoid over compression of transforaminal sacral fractures and sacral nerve root injury.

For open reduction, a minimal invasive short posterior longitudinal skin incision was made slightly lateral to the midline. The fascia was opened longitudinally without cutting the muscles. The sacral fracture line was cleaned. Indirect decompression of sacral nerve roots was performed with fracture reduction and directly when preoperative CT showed bony fragments in the sacral nerve root canal. Iliosacral screws were inserted percutaneously through a separate small skin incision lateral to the PSIS (**Fig. 6**). Minimally displaced (< 5 mm) lateral sacral fractures were treated with closed reduction techniques and percutaneous iliosacral-screw fixation on the prone position. The screws should pass the midline of the sacrum.
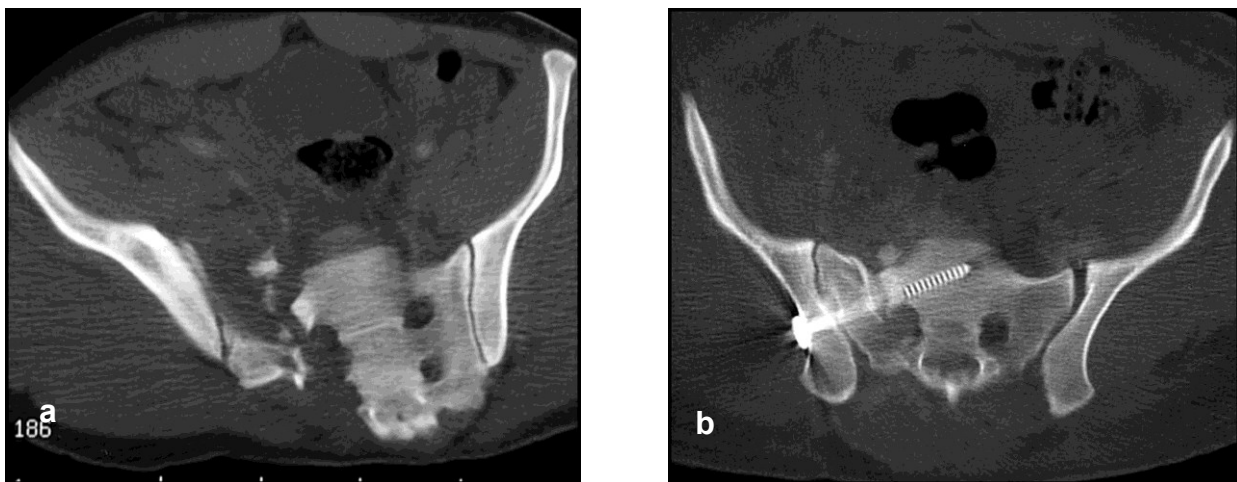
Figure 6. Open reduction and iliosacral-screw fixation of a displaced transforaminal sacral fracture. (a) CT image shows the fracture before treatment. Reduction was performed through a short, dorsal vertical incision, close to the midline. (b) CT image of the fracture, after percutaneous iliosacral-screw fixation through a lateral-stab skin incision.

Sacroiliac dislocation and fracture dislocation (61-C1.2)

SI-joint injuries were most often operated from the front in the supine position. The approach was made using skin incision along the iliac crest extending posterior to the iliac tubercle. The incision and opening the abdominal wall muscles stopped to the ASIS to avoid damage to the lateral femoral cutaneous nerve. The external oblique abdominis muscle was opened along its fibers and the inner abdominal wall muscles were sharply detached from the iliac crest. Sharp removal of the insertion of the iliacus muscle from the iliac crest and subperiosteal detachment of the muscle was carried out

along the iliac wing, down to the pelvic rim and posteriorly as far as the SI-joint. Once the disrupted SI-joint was identified, dissection proceeded upward to the sacral ala. The dissection proceeded gradually in a medial direction, staying beneath the periosteum and muscle on the sacral ala. The anterior lateral part of the sacrum was exposed carefully to avoid traction of the L5 nerve root, which is located 2 to 3 cm medial to the SI-joint (Matta and Saucedo 1989, Tile 1995). Flexion of the hip joint relaxes the psoas muscle and the medial muscles of the abdominal wall, thus improving the exposure. While dissecting the superior gluteal notch, great care is taken to avoid damage to the superior gluteal artery and nerve.
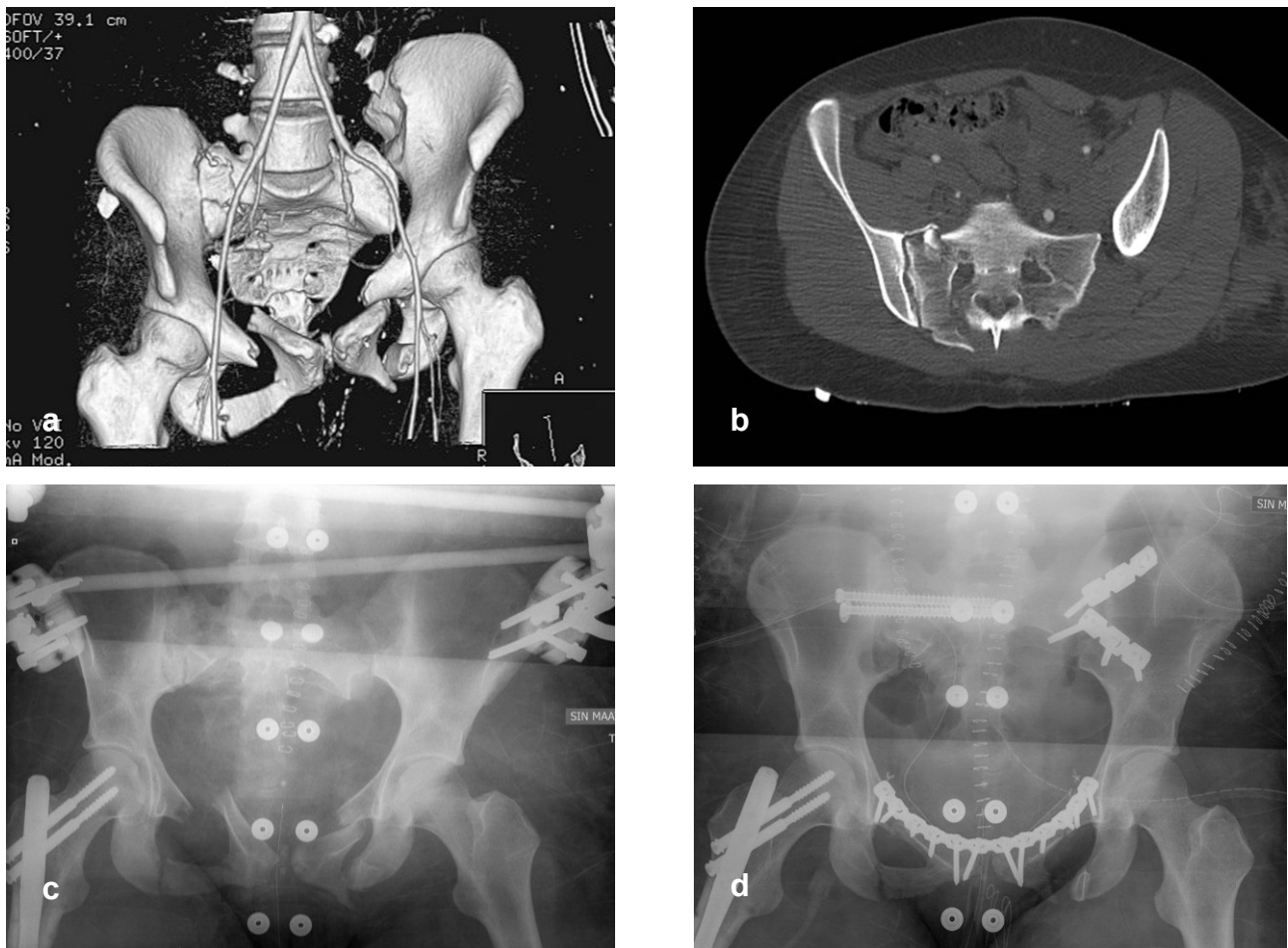
Figure 7. Procedure for fixing a type C3 pelvic ring injury. (a and b) This pelvic injury includes a transforaminal (zone II) sacral fracture on the right side, complete dislocation of the left SI-joint, bilateral fractures of the rami, and disruption of the symphysis. (a) 3D-image reconstruction, anterior view; (b) Contrast-enhanced CT image. (c) X-ray image shows closed reduction and provisional stabilization of the fractures, performed with an anterior external fixation frame. (d) X-ray image shows results of a staged reconstruction of the pelvis. In the first stage, the patient was placed in the supine position, and simultaneous with an open reduction, the left SI-joint was fixed with two anterior plates and injuries to the anterior pelvic ring were stabilized with plate fixation. In the second stage, the patient was placed in the prone position, and during open reduction, the sacral fracture was stabilized with percutaneous iliosacral screw fixation.

Following dissection, the displaced SI-joint was reduced. Reduction was carried out by inserting two 4.5-mm cortical screws on either side of the SI-joint and by using either the Farabeuf clamp or the pelvic reduction clamp. For fixation, two 4.5-mm reconstruction plates or 4.5-mm DC plates were used (**Fig.7**). Three holes plates, one hole on the sacral side and two on the iliac wing side, were used. The first step of anterior plate fixation technique was to fix the plate to the sacrum ala with one screw. Reduction of the displaced hemipelvis was finalized using the plate as a guiding instrument. The remaining cap in the SI-joint was reduced using lateral compression and dynamic compression technique while drilling the two remaining screws into the iliac wing. The angle between the two anterior plates should be 60 to 90 degrees to avoid vertical redisplacement of the injured hemipelvis.

Iliosacral screws were only used to fix the SI-joint at the beginning of this study, because the control of reduction of the SI-joint using posterior approach with the patient in the prone position was difficult with mere finger palpation through the sciatic notch only.

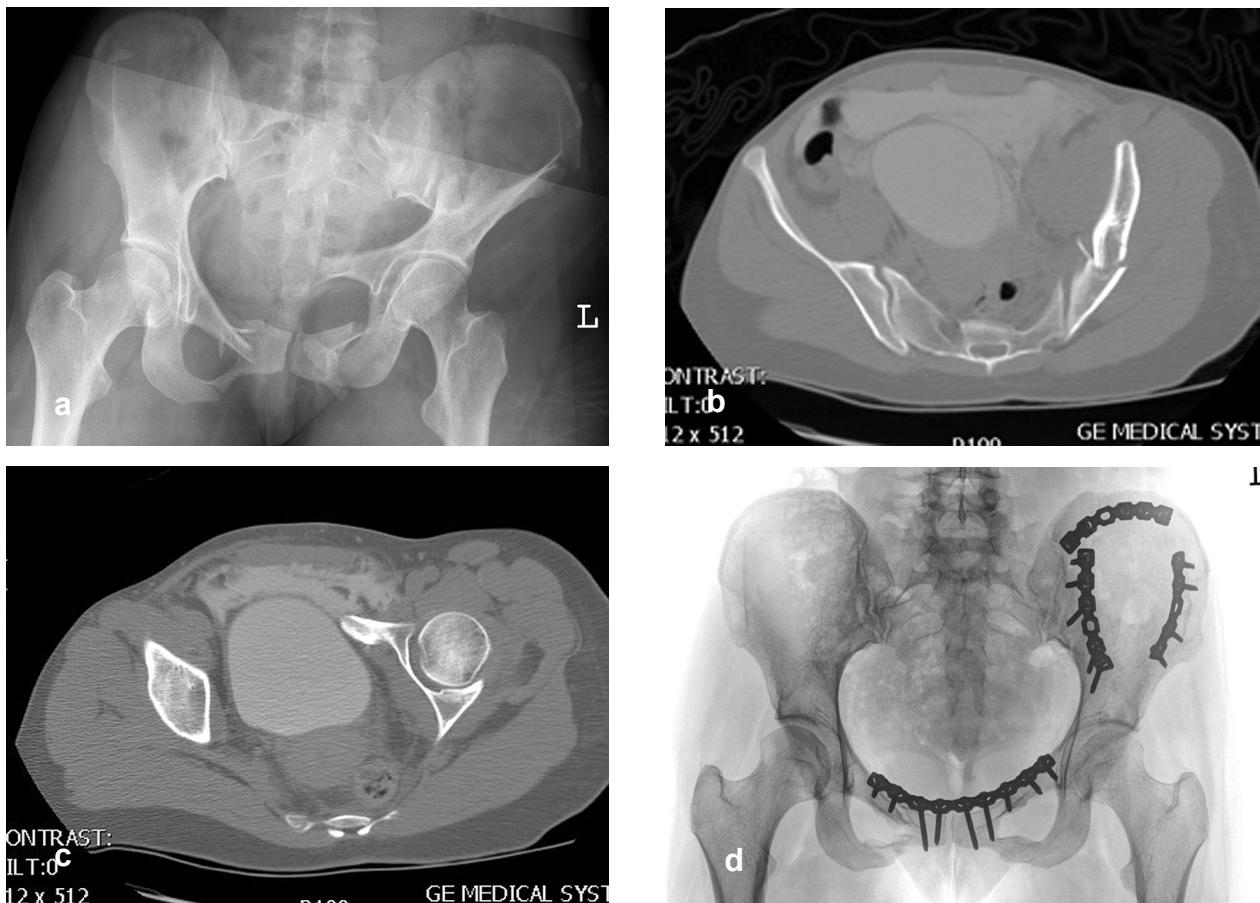Figure 8. Treatment of a C1.1 pelvic ring injury with extraperitoneal rupture of the bladder. (a) X-ray and (b, c) CT images with contrast enhancement show the extent of the injury. (d) Simultaneous with reduction, fixation of the posterior iliac fracture and bilateral pubic rami fractures were performed together with saturation of the bladder in the early phase of the injury, with an excellent clinical outcome.

Transiliac fractures (61-C1.1)

Transiliac fractures were fixed through the same approach along the iliac crest as described to SI-joint injuries. 3.5-mm reconstruction plates (**Fig. 8**) or long 3.5-mm cortical screws were used with interfragmental compression. First, an anatomically bended reconstruction plate was fixed with screws on the posteromedial side of the fracture. Next, the iliac fracture was reduced with a reduction clamp placed between the free lateral end of the plate and the ASIS. Reconstruction was completed by drilling the last screws into free lateral holes of the plate. Two plates were used; one close to the lateral iliac crest and one close to the pelvic rim (**Fig. 8**).

Post-operative care in type C injuries

Mobilization with crutches commenced within 1-2 days for type C1 injuries without weight-bearing on the injured side. Full weight-bearing began after 8-12 weeks. The load was increased gradually based on the fracture type and radiographic follow-up. In bilateral type C3 injuries, walking exercises with crutches commenced after 8-12 weeks, based on the type of the posterior pelvic injury.

4.6. Internal fixation of anterior pelvic ring injuries

Symphysis pubis disruptions

The SP was exposed through either a vertical or a transverse Pfannenstiel's type skin incision (Matta and Saucedo 1989, Hirvensalo et al. 1993). A vertical incision was chosen when the anterior fixation was combined with laparotomy. Because of cosmetic reasons, a transverse skin incision was the choice for symphyseal disruption. The midline between the rectus abdominis muscles was opened, and the prevesical space was exposed. The insertions of the rectus abdominis muscles could be incompletely detached from the pubis on their inner aspects, whereas their lateral and outer parts of attachments were left intact. The symphyseal plates (two 3.5-mm reconstruction plates) were placed under the rectus sheet (**Fig. 9**).
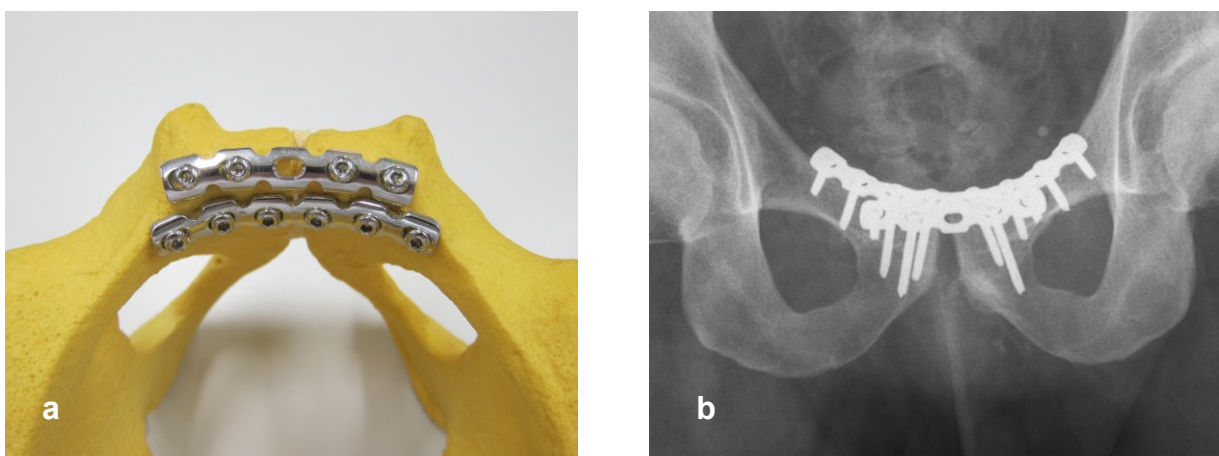

Figure 9. Fixation of the disrupted (wide diastases) symphysis pubis described in Study III. The disruption was reduced and fixed with two 3.5-mm reconstruction plates. (a) A model shows the placement of the plates on the bones for reconstruction; (b) an x-ray image shows the placement below the rectus muscles.

Pubic rami fractures

Displaced fractures of the pubic rami were approached through an anterior extraperitoneal approach (Hirvensalo et al. 1993). The approach was created through a low midline incision starting from the SP extending up with the patient in the supine position. A Phannenstiel type transversal skin incision did not allow enough space to operate on the lateral aspect of the inner pelvis. The space between the rectus abdominis muscles was opened and the prevesical extraperitoneal area was exposed. The peritoneum was left intact. The bladder, marked with a catheter balloon, was pushed gently posterior. Insertions of the rectus abdominis muscles were not detached from the pubis. Dorsal periosteal tissue of the muscle attachment could be partially released to create proper space for a fixation plate. Anterior and lateral attachments of the rectus muscles were always left intact.

Subperiosteal dissection below the abdominal muscles was continued laterally on the superior ramus following the inner and cranial aspects of the pelvic brim. By remaining close to the bone and by using subperiosteal stripping only, injuring essential structures could be avoided. Corona mortis vessels, on the inner aspect of the superior ramus and close to the outer border of the obturator foramen, were ligated whenever they were present. The iliopectineal fascia and other periosteal attachments on the brim were detached, which allowed for elevation of the iliopsoas muscle with the neurovascular structures. This maneuver provides a good view of the entire superior ramus, the anterior and inner side of the anterior column, and the quadrilateral area. The external iliac vein (the most medial vessel) was usually visible on the anterolateral side of this approach and easily recognized. The external iliac vein, the external iliac artery, the femoral nerve, and the iliopsoas muscle were lifted and drawn laterally all together with a hook. No dissection or separation of these vulnerable structures was necessary. The underlying obturator nerve and vessels entering the obturator foramen were identified and protected and left posteriorily. In bilateral rami fractures both sides were exposed.

After reduction, the rami fractures were fixed with an anatomically curved 3.5-mm reconstruction plate placed along the pelvic rim (linea terminalis). For fixation of lateral fractures of the superior ramus, a longer reconstruction plate was used extending the supra-acetabular level where two screws were inserted through the same approach (**Fig. 10**). An alternative fixation method for simple transverse superior rami fracture with good bone quality, is using a long intramedullary 3.5-mm cortical screw. Bilateral rami fractures were fixed either by using two separate plates, one on each side, or with one longer plate over both rami fractures and the SP (**Fig. 7**). Concomitant acetabular fractures involving the anterior column were reduced and fixed through the same approach.

4.7. Lumbopelvic fixation of spinopelvic dissociations

Operative technique

A staged reconstruction was performed when a combined H-shape sacral fracture and an additional anterior pelvic ring injury was present. The injuries of the anterior part of the pelvic ring were most commonly operated on first using an anterior approach (Hirvensalo et al. 1993) (**Fig. 10**). The method for lumbopelvic fixation includes two pairs of 6-mm lumbar pedicle screws, bilateral 6-mm

longitudinal rods, one or two transverse connectors, and two pairs of 8-mm iliac screws. A dorsal midline approach was used. Longitudinal rods were connected to L4 and L5 pedicle screws after having been contoured to lie close to the posterior lamina of the sacrum and medial to the PSISs. One or two transverse connecting rods between longitudinal rods were used to secure the fixation. The operative reduction and correction of displacements and rotational deformities of both hemi-pelves and the caudal segment of the sacrum were performed using two pairs of reduction clamps and caudal distraction of the distal part of the sacrum. The distal end of the longitudinal rods and the superior aspect of the posterior iliac crests are the insertion points for the first pair of reduction clamps bilaterally. The longitudinal rods fixed to pedicle screws act as a counter force for the final vertical correction of the sacral fracture components. Simultaneous reduction of the hemipelves into a dorsal direction by traction was performed by the second pair of reduction clamps placed in the

Figure 10. Treatment of an H-shaped sacral fracture with spinopelvic dissociation in a 34 year-old male that was run over by a car. (a,b) Bilateral rami fractures associated with the H-shaped sacral fracture with spinopelvic dissociation are shown in 3D-reconstructed images of (a) the anterior and (b) the posterior pelvis. (c) Contrast-enhanced CT image shows the bilaterally fractured posterior ring structure. (d) X-ray image shows the result of the two-stage pelvic reconstruction. The first stage consisted of anterior pelvic ring fixation; the second stage consisted of a segmental lumbopelvic fixation. An additional iliosacral-screw was placed with the percutaneous technique to fix the transiliac fracture dislocation of the right SI-joint.

Figure 11. Treatment of an H-shaped sacral fracture with spinopelvic dissociation without an anterior injury to the pelvic ring in a 37-year old male, who fell from the fifth floor. (a) 3D-image reconstruction and (b) CT

image show displaced bilateral vertical transforaminal sacral fractures, which caused L5 and S1 nerve root injuries and resulted in severe motor deficiencies of the lower legs. (c) CT image shows a type 3b transverse sacral fracture with complete translational fracture displacement between S1 and S2, which caused cauda equina deficits. (d-f) X-ray images and (g-h) CT images show the results of pelvic reconstruction. (d) AP, (e) inlet, (f) outlet views; (g) sagittal, and (h) axial views. Treatment included an operative reduction and lumbopelvic fixation with sacral laminectomy, performed 5 days later, when the patient was hemodynamically stable. A clear neurological recovery was detected, and after long rehabilitation, the patient was able to return back to work. At the end of follow-up, 6 years from the accident, the patient had no pain, but reported deficiencies in micturition and slight bowel incontinence; therefore, the POS clinical outcome was graded fair.

PSIS on both sides. To achieve this goal, simultaneous bilateral manual femoral traction and hyperextension of both hip joints were also used. When accurate reduction was obtained, the lumbar spine and central upper sacral segment was fixed to the pelvic ring by placing two pairs of 8-mm iliac screws into the iliac bones with the Galveston technique (Allen and Ferguson 1982) and connecting them to the longitudinal rods with special clamps.

Indirect decompression of the lumbar (vertical fracture lines) and sacral neural roots (the transverse fracture line) was achieved through reduction of all the sacral fracture components (**Figs 10, 11**). Direct decompression by sacral laminectomy was performed for all completely displaced transverse sacral fracture with occlusion of the central sacral canal (**Fig. 11**) and in the patients in which a clear translational displacement remained in the transverse fracture line after the final reduction as assessed by a true lateral sacral fluoroscopic view. In cases with comminuted sacral lamina (floating dorsal sacrum) and/or good sagittal alignment after the final reduction, sacral laminectomy was not performed. Posterolateral arthrodesis across the instrumented lumbosacral levels was not performed because the internal fixator was planned to be removed later.

Post-operative care

Lumbopelvic fixation provides adequate stability to permit early bed to chair transfer and sitting. Ambulation and weight-bearing after lumbopelvic fixation of spinopelvic dissociation is possible within pain limits and when allowed by the associated lower extremity injuries. From the beginning of this study, until the end of the 21th century, full weight-bearing was started after 8-12 weeks. During the last study years, ambulation and weight-bearing within pain limits was start
ed earlier, when the associated lower extremity injuries allowed.

4.8. Radiological analysis

Pelvic ring injuries

The vertical displacement of all fracture components in type C injuries was measured from pelvic AP radiographs (**Studies I** and **III-IV**). The AP displacement (posterior injury) was determined from CT scans (Gill and Bucholz 1984). In addition, vertical displacement and/or overlapping of rami fractures and/or symphyseal disruption in type B lateral compression injuries and vertical displacement and diastasis of symphyseal disruption in open book injuries were measured from AP plain radiographs. The measurements were made from radiographs taken before primary treatment,

after reduction and external or internal fixation, after the removal of the external fixation frame, and in the final follow-up visit. The AP displacement of the anterior pelvic ring injury could not be measured reliably from the CT scans. Radiological result was graded by the maximal residual displacement in the posterior or the anterior pelvic ring injury as: excellent (0-5 mm), good (6-10 mm), fair (11-15 mm), and poor (more than 15 mm).

Spinopelvic dissociations

The kyphotic angulation of the transverse sacral fracture component of the H-shaped sacral fracture was measured from the lateral sacral radiographs and/or the sagittal CT reformations by measuring the angle between the posterior sacral cortices superior and inferior to level of the transverse fracture. The translation of the transverse sacral fracture was also determined from these views by measuring the displacement of the posterior cortex of the sacrum above and below the transverse fracture. The measurements were performed from pre-operative, post-operative, and final radiographs and CT images.

4.9. Outcome evaluation

Clinical assessment

All patients in **Studies I, III,** and **IV** had a clinical examination with particular attention to their gait and the lower extremity sensory and motor function to identify injuries to the lower lumbosacral plexus. Lower extremity neurological motor deficit was graded by the six-point (0-5) Medical Research Council (MRC) scale (1981). A rectal examination was performed to evaluate the sphincter contraction and light touch sensation was assessed for the perianal dermatomes of S2 to S5 pre- and postoperatively.

Neurological assessment

In **Study IV**, the neurological deficits (Denis zone II and III sacral fractures) were classified according to Gibbons et al. (1990). On the Gibbons scale, grade 1 denotes no neurological abnormality, grade 2 paresthesias only, grade 3 motor loss with intact bowel and bladder function, and grade 4 bowel and/or bladder dysfunction (with or without motor or sensory loss). Improvements in neurological function were assessed at final follow-up using the Gibbons criteria.

Pain

Chronic pain problems in the pelvic ring and in the lower extremity at final follow-up (**I,III,** and **IV**) were graded according to the Majeed's scoring system (*1989*) as: no pain, mild (intermittent, normal activity), moderate (limits activity, relieved by rest), and severe (continuous at rest, intense with activity).

Functional outcome

The functional outcome from **Studies I** and **III** was measured using a modification of the scoring system described by Majeed (1989). Ability to work was separated from the original score giving a

maximal total score of 80 points for each patient (instead of 100 points for working and 80 points for non-working patients), in order to compare the outcome of different fracture types and sub-groups. The original scoring system was modified to focus on the outcome after unstable pelvic ring injury and not the handicap caused by additional musculoskeletal or other system injuries. The total score reflecting the functional outcome was also modified to specifically reflect the outcome after the pelvic injury (**Table 6**). However, Majeed score was not used in **Study IV**, since neurological impairments, such as bladder and bowel disturbancies, are not integrated into this score although they have relevant prognostic influence on outcome.

Table 6. Functional outcome total score modified after Majeed (1989).

Total score	Working before injury [a] Points (0-100)	Not working before injury [a] Points (0-80)	Modified score Points (0-80)
Excellent	85 to 100	70 to 80	78 to 80
Good	70 to 84	55 to 69	70 to 77
Fair	55 to 69	45 to 54	60 to 69
Poor	0 to 54	0 to 44	0 to 59

[a] Majeed's original functional grading based on a score out of 100 points for working and 80 points for non-working patients (1989)

Pelvis outcome scale (POS)

In **Study IV**, the clinical outcome was evaluated using the clinical component of the three criteria of German multicentre study group pelvis outcome scale (POS/GMS1 scale) (Pohlemann et al. 1996). The rating of the clinical result (1-4 points) was classified as good or poor outcome. A POS clinical score of 3-4 points was considered a good outcome while 1-2 points was a poor outcome. The total result after the pelvic ring injury by summarizing the radiological (3 points) and clinical results (4 points) was measured in **Study III.**

4.10. Statistical analyses

Study I. The BMDP software package V 7.0 (Universty of California, Berkeley) was used for the statistical analysis. The data are expressed as frequency and median. The effect of fracture dislocation on late pain was evaluated by Fisher's exact two-tailed test. The Mann-Whitney rank sum test was used for comparison of functional results between the subgroups. A p-value < 0.05 was considered statistically significant.

Study II. The statistical comparisons of the clinical parameters were performed with SPSS 14.0 for Windows (SPSS, Inc., Chicago, IL). The results are expressed as means ± SD for continuous non-skewed variables. For skewed variables the results are expressed as median with 25 and 75 percentage quartiles and as frequencies or percentages for categorical variables. Continuous variables between the groups were compared by the Mann-Whitney U test. The frequency distribution of the

categorical variables was compared between the groups with the Chi-square test. The statistically significant level was set as $p < 0.05$ (two-tailed). The relationships of clinical characteristics were examined by Pearson's correlation analysis.

Study III. All statistical evaluations were performed using SPSS 11.0.1 for Windows®. The multiple logistic regression analysis (Cox regression) with the forward stepwise method was used in order to detect independent factors correlating to the outcome. Both crude and adjusted odds ratios with 95% confidence intervals are reported, and values excluding number one are considered as statistically significant.

Study IV. The statistical analysis of the clinical parameters was performed with SPSS 21.0 for Mac (SPSS, Inc., Chicago, IL). Continuous variables between the groups were compared by the Mann-Whitney U-test while frequency distribution of categorical variables was compared between the groups with the Chi-square test. Statistical significance was set at $p < 0.05$ (two-tailed).

5. RESULTS

5.1. Outcome of type B and C pelvic ring injuries treated with a trapezoid compression frame

The mean time for application of the frame and closed fracture reduction was 39 (range, 15-105) minutes. A rereduction was considered necessary for seven patiants. In four patients with type C injury, an additional femoral or tibial traction was used for 6 to 8 weeks. The frame was removed after a mean of 6.4 (range, 6-11) weeks. The mean hospital stay was 47 (range, 7-180) days.

Complications of the treatment

Fracture malunion (displacement > 10 mm) was found in 64 of the 110 patients (**Table 7**). Infection at the pin sites was seen in 26 patients, which for three patients was regarded as a deep infection with radiological signs of osteitis. These were treated with debridement and antibiotics. Injury of the lateral femoral cutaneal nerve with a permanent sensory defect was found in two patients. The site of the pins was considered to be too distal on the ASIS. Three patients had a sacral pressure sore. One required operative treatment with a musculocutaneus flap.

Table 7. Complications of external fixation of type B and C pelvic ring injuries in 110 patients.

Early complication	Patients	
Loss of reduction (alignment)	63	57 %
Superficial pin site infection	23	21 %
Pin loosening	2	2 %
Lateral femoral cutaneous nerve injury	2	2 %
Late complication		
Fracture malunion	64	58 %
Nonunion	6	5 %
Deep pin site infection	3	3 %
Sacral pressure sore	3	3 %

Type B open book injuries

The diastasis of the symphysis pubis improved from a mean of 39 (range, 16-70) mm to 19 (range, 0-44) mm, but in two patients the end radiological result was worse than in the beginning (**Table 8**). The final radiological result was graded as good in two patients and fair or poor in 6 patients (**Table 9).** In 5 patients, an additional vertical displacement (3-22 mm) occurred at the symphysis which could not be corrected by closed reduction techniques. In these patients, sacral pain was still present at the final follow-up (**Tables 10 and 11**) and the final functional outcome was unsatisfactory in

four (**Table 12**). The three patients without vertical displacement at the symphysis had no pain and their functional outcome was excellent despite mild residual symphyseal diastasis of 6 to 26 mm. Two patients had a lesion of the lumbosacral plexus with urological deficiencies and one had paresis of a lower limb and an unsatisfactory functional result. There was permanent instability in one patient for whom the frame had been removed at 4 weeks because of a deep pin tract infection.

Table 8. Radiological end results compared with primary fracture displacement in patients with type B and C pelvic ring injuries (n=110).

Fracture type	Patients	Radiological end result		
		Better	Same	Worse
Type B open book	8	6	0	2
Type B lateral compression	62	1	38	23
Type C	40	1	1	38

Table 9. Radiological end results after external fixation of type B and C pelvic ring injuries (n=110).

Fracture type	Patients	Radiological end result			
		Excellent	Good	Fair	Poor
Type B open book	8	0	2	1	5
Type B lateral compression	62	29	13	16	4
Type C	40	0	2	9	29

Type B lateral compression injuries

In two-thirds of patients with lateral compression injuries, the displacement of the fractures of the rami was successfully reduced primarily, but redisplacement occurred in all during the first few weeks. For eight patients, the position was made worse by the closed reduction and external fixation. The amount of fracture displacement became worse in one-third of patients during the period of the external fixation (**Table 8**), and in nearly all these patients the end radiological result was fair or poor (**Table 9**). At the final follow-up, 34 patients (55%) were free from pain (**Tables 10, 11**).

Poor radiological results were associated with poor functional results (**Tables 9, 12**). In those 42 patients who had vertical displacement and shortening of more than 10 millimeters at the fracture of the pubic rami, pain was more common and intense (p = 0.01) and the functional result worse (p = 0.002) than in those 20 patients with less displacement.

Table 10. Chronic pain after external fixation of type B and C pelvic ring injuries (n=110).

Fracture type	Patients	Chronic pain			
		No	Mild	Moderate	Severe
Type B open book	8	3	2	3	0
Type B lateral compression	62	34	24	2	2
Type C	40	3	18	13	6

Table 11. Localization of pain in the pelvic ring at the end of follow-up (n=110).

Fracture type	Patients	Pain localisation			
		No pain	Anterior	Posterior	Ant. & post.
Type B open book	8	3	0	4	1
Type B lateral compression	62	34	4	16	8
Type C	40	3	2	29	6

Table 12. Functional results after external fixation of type B and type C pelvic ring injuries (n=110).

Fracture type	Patients	Functional result (Modified Majeed score)			
		Excellent 78 - 80	Good 70 - 77	Fair 60 - 69	Poor < 60
Type B open book	8	3	1	2	2
Type B lateral compression	62	28	18	11	5
Type C	40	3	3	13	21

Type C injuries

The degree of fracture displacement increased in all except two of the 40 patients during the period of external fixation (**Table 8**). The average vertical displacement in the posterior pelvic ring injury increased during the external fixation from 8.9 (range, 3-30) mm to 15.2 (range, 5-30) mm. Vertical displacement of the fractures of the rami or of the disrupted symphysis increased from a mean of 10.0 (range, 0-25) mm to 12.4 (range, 0-30) mm and the shortening increased from a mean of 6.1 (range, 0-20) mm to 12.4 (range, 0-30) mm. Thirty-seven patients (92.5%) had chronic pain (**Tables 10, 11**).

In the 30 patients who had vertical displacement of more than 10 mm at the posterior injury to the pelvic ring, the functional result was significantly worse (p = 0.02) and pain was more common and intense than in 10 patients with vertical displacement of 5 to 10 mm. No influence on the pain or functional result was seen in the latter group relative to the amount of residual displacement of the injury to the rami and symphysis.

The functional result was unsatisfactory (fair or poor) in 34 patients (85%) (**Table 12**). It was associated with an incomplete reduction of the fracture (**Table 13**), and also with injury to the lumbosacral plexus for 14 patients. A lesion of the lumbosacral plexus was more often connected with sacral fractures (11/27) and dislocation or fracture dislocation of the SI-joint (4/7) than with transiliac fractures (1/6).

Table 13. Functional results compared with radiological results in 40 patients with type C injuries treated with external fixation.

Radiological result	Functional result (Modified Majeed score)				Totals
	Excellent	Good	Fair	Poor	
Excellent	0	0	0	0	0
Good	1	0	0	1	2
Fair	0	1	4	3	8
Poor	2	2	9	17	30
Totals	3	3	13	21	40

5.2. Outcome and early prognostic mortality-related factors of arterial pelvic hemorrhage treated with TAE

The study population consisted of 46 pelvic ring and 3 acetabular fractures. The three (6%) acetabulum fractures included two both-column fractures and one anterior-column fracture with central dislocation of the femoral head. In addition, both-column acetabulum fracture patients had a concomitant type B lateral compression injury on the contralateral side.

Control of bleeding

External fixation or the pelvic binder application was the primary intervention in 17 patients and the second procedure in 10 patients. The first emergency operation was laparotomy in 6 and lower extremity bleeding control in 4 patients. Three patients had laparotomy after TAE. One patient had symphysis plate fixation during laparotomy. Preangioembolization pelvic stabilization (regardless of the method used) did not correlate with survival. Seven decompressive laparotomies were performed due to abdominal compartment syndrome occurring after TAE.

The long median interval (183 min, IQR 133-263 min) from admission to TAE (door to angio time) is reflected by 10 patients who underwent the other bleeding control procedures prior to TAE. The nonsurvivors tended to have a shorter door to angio time than the survivors (183 ± 94 min vs. 283 ± 269 min), but the difference was not statistically significant (p = 0.27). The total average length of stay in the angio suite was 178 ± 55 min, with no difference between the survivors and nonsurvivors. Bleeding control with TAE was achieved in all patients except for one with a rupture of the external iliac artery, which was treated with surgical reconstruction after diagnosis by angiography.

Characteristics of bleeding arteries

Angiography revealed one bleeding artery in 21 patients (43%) and multiple (two or more) arterial bleedings in 28 patients (57%). Fifteen patients (31%) had bilateral arterial bleedings. The obturator artery was the vessel injured most commonly. The detailed fracture classification and the relationship between bleeding arteries (the largest bleeding artery in each patient) and mortality according to pelvic fracture type is presented in **Table 14** and an overview of the bleeding arteries in **Table 15**.

Table 14. The relationship between bleeding arteries (the largest bleeding vessel in each patient) and mortality according to the pelvic fracture type (n=49).

Fracture type	Patients	Bleeding arteries			Nonsurvivors
		Large [a]	Medium [b]	Small [c]	Patients
Type C injuries	38	7	16	15	11
Type B open book injuries	2	0	0	2	0
Type B lateral compression	5	0	1	4	0
Type A2 Iliac wing fracture	1 [d]	0	1	0	1
Acetabulum	3	0	2	1	2
Totals	49	7	20	22	14

[a] Large artery; main trunk of internal or external iliac
[b] Medium size arteries; superior gluteal, inferior gluteal
[c] Small size arteries; iliolumbar, sacral, obturator, pudendal, vesical, and femoral circumflex
[d] 92 year-old male with a comminuted type A fracture of the iliac wing

Thirty-day mortality

The overall 30-day mortality was 29%. Half of the patients died within 24 h of admission (**Table 16**). None of the patients died due to ongoing pelvic bleeding, but five of the early bleeding-related deaths occurred due to the irreversible lethal triad of acidosis, hypothermia, and coagulopathy, regardless of whether the primary bleeding was controlled with TAE. Three of the six patients (50%) who underwent an emergency laparotomy died (one due to the lethal triad of acidosis, hypothermia, and coagulopathy; one due to a head injury; and one due to MOF). The overall mortality in patients

Table 15. Source of pelvic fracture-related arterial bleeding in 49 patients with blunt pelvic trauma.

Bleeding artery	Patients	
Internal iliac artery	**42**	**86 %**
Main trunk	6	12 %
Main branch	36	74 %
External iliac artery	**2**	**4 %**
Main trunk	1	2 %
Main branch (femoral circumflex artery)	1	2 %
Internal and external iliac arteries	**5**	**10 %**
Main trunk of internal iliac artery and femoral circumflex artery	1	2 %
Main branch of internal iliac artery and femoral circumflex artery	4	8 %

Table 16. Causes of early or late deaths after pelvic arterial bleedings treated with TAE (n=49).

Pt	Gender	Age Yrs	Fracture type	Pelvic bleeding	Bleeding vessels	Time of death	Cause of death
Early deaths (< 24 h)							
1	F	28	C1	unilateral	MSS	5 h	Head injury
2	F	37	BC + B2	bilateral	MMSS / MSSS	5 h	Bleeding related [a]
3	F	61	C1	unilateral	SSS	7 h	Bleeding related [a]
4	F	27	C1	unilateral	L	7 h	Bleeding related [a]
5	F	66	C1	bilateral	L / S	10 h	Bleeding related [a]
6	M	19	C1	bilateral	M / S	12 h	Head injury
7	M	66	C3	unilateral	MS	15 h	Bleeding related [a]
Late deaths (1 to 30 days)							
8	F	72	C1	bilateral	M / S	2 days	Head injury
9	M	22	C1	bilateral	LSS / SS	3 days	Head injury
10	M	92	A2	unilateral	M	3 days	MOF [b]
11	F	28	C3	unilateral	L	3 days	Cardiac arrest [c]
12	M	24	C2	bilateral	MSSS / S	7 days	MOF [b]
13	F	74	BC + B2	bilateral	S / M	11 days	Head injury
14	M	76	C1	unilateral	MS	22 days	MOF [b]

L Large artery*; M* Medium size artery*; S* Small size artery

BC+B2 Both column acetabulum fracture with central dislocation of the femoral head on one side and type B lateral compression pelvic ring fracture on the other side

[a] Irreversible lethal triad of acidosis, hypothermia and coaculopathy, regardless of whether the primary pelvic bleeding was controlled with TAE

[b] Prolonged hypovolemia-related multiple organ failure

[c] Unspecified cardiac arrest

with concomitant intra-abdominal bleeding necessitating laparotomy was 44%, whereas the overall mortality in patients without intra-abdominal bleeding was 25%.

Survivors versus nonsurvivors

Eleven of the 14 deaths occurred in patients presenting a type C pelvic ring fracture (**Table 14**). There was no mortality related to type B open book injuries or lateral compression injuries. In patients suffering from a fall from height, the height of the fall was significantly higher in the nonsurvivors (n = 6) than in the survivors (n = 13): 17.5 ± 5.3 m versus 10.7 ± 4.5 m (p = 0.017). Age, ISS, or NISS did not predict the survival of the patient.

There was no statistically significant difference in the first laboratory parameters recorded in the survivors and nonsurvivors when all patients were considered. However, after excluding the patients dying from head injuries, some clinically feasible parameters for identifying the nonsurvivors became evident (**Table 17**). The results were also analysed by plotting a receiver operating characteristic curve in order to obtain sensitivity and specificity values. A reasonable cut-off value was identified only for the admission BE (base excess). When a BE cut-off value of -10 mmol/l was used, the sensitivity and specificity were 75% and 62.5 %, respectively.

Table 17. Laboratory parameters that were statistically significantly different on admission between survivors and nonsurvivors after excluding the five patients dying from head injuries (n=44).

Parameters	Survivors n=35	Nonsurvivors n=9	p-value
BE 1, mmol/l	-6.9 ± 4.5	-13.7 ± 7.9	0.024
Platelets 1	188 ± 71	127 ± 64	0.042
TT% 1	62 ± 23	44 ± 18	0.038

Result are the mean ± SD for continuous, unskewed parameters

BE base excess, *1* the first measured value, *TT%* thrombin time

Bleeding arteries and outcome

All seven disruptions of large pelvic arteries were seen among type C pelvic ring injuries (**Table 14**). Patients with a large vessel injury (internal or external iliac artery) had a significantly lower BE on ER admission than the patients with medium- or small-size injuries (-14.0 ± 5.9 versus -7.2 ± 5.3, respectively; p = 0.011). The values of other parameters on admission failed to reach statistical significance when comparing these two patient groups. Four of the 7 patients with a large vessel injury died (mortality 57%) compared to 10 of 42 (24%) of those with a medium- or small-vessel injury. The difference did not reach statistical significance (p = 0.07), which could be due to the low number of patients (type II error). The bleeding vessel size scores were significantly higher for the nonsurvivors than the survivors (p = 0.004). This was also seen after omitting the nonsurvivors who died due to head injury (p = 0.020).

Complications

The overall angioembolization-related complication rate was low. In one case, the signs of late bleeding prompted a repeat angiography, which revealed a new bleeding artery not seen in the first angiography. Unilateral necrosis of the gluteal muscle was seen in one patient. The etiology of ischemia of the gluteal muscle in this case was either the embolization of the internal iliac artery or direct impact and compartment syndrome of the buttock. One patient had hemorrhage at the puncture site, which was treated with direct suturation.

5.3. Outcome of operatively treated type C pelvic ring injuries

Based on the Tile's classification there were 40 type C1.3, 16 type C1.2, 24 type C1.1, 13 type C2, and 8 type C3 injuries. All patients had posterior internal fixation except five, in whom only anterior fixation was used because of minimal initial displacement (< 5 mm) of the posterior pelvic ring injury. Two of these patients had a bilateral type C3 injury, in whom ORIF was only used unilaterally. In the anterior part of the pelvic ring, internal fixations were used in 74 patients and external fixation in 4 patients. Altogether 108 iliosacral screws were inserted in 55 patients, 17 of which (13 patients) were inserted percutaneously without open reduction of the fracture. The other posterior injuries were stabilized with plate osteosynthesis. Altogether 103 posterior and 77 anterior internal fixations were performed in 101 patients.

Radiological results

The preoperative vertical or AP displacement in the posterior or anterior pelvic ring injury was more than 10 mm in all patients (range, 10–60 mm). The final radiological results were excellent or good in 91 patients (90%), and fair in 10 patients (10%). Of 10 patients with a fair radiological result, 6 had a failure of the primary fixation. In 4 of these patients, the fixation failed in the posterior pelvic ring, while in 2 patients it failed in the anterior pelvic ring. In 2 patients, the minimally displaced and unfixed sacral fracture dislocated more after ambulation without weight bearing on the injured site, and united in an unsatisfactory position. In 2 other patients, the position of the initially minimally displaced (< 10 mm) and unfixed anterior pelvic ring injury showed increased displacement although the posterior injury was adequately stabilized.

Functional results

According to the modified Majeed score, the functional results were excellent in 68 patients (67%), good in 16 patients (16%), fair in 16 patients (16%), and poor in one patient (1%). Excellent or good functional results were positively affected by anatomical or nearly anatomical reduction (**Table 18**). Unsatisfactory (fair or poor) functional results were in conjunction with associated lumbosacral plexus injuries in 10 of 17 patients. In one of 17 patients the unsatisfactory functional result followed a nonanatomic reduction, and in one it followed spinal stenosis not associated with the pelvic fracture. The only poor functional result followed traumatic thigh amputation. In 4 patients, the functional results were unsatisfactory because of late pain in the posterior part of the pelvic ring

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despite the fact that the reduction result was satisfactory. Thirty-four of 101 patients (34%) had late pain problems and in 33 of them the pain was mainly located in the posterior part of the pelvic ring.

Table 18. Functional results compared with radiological results after operative treatment of type C pelvic ring injuries (n=101).

Final radiological result	Functional Result (Modified Majeed score)				Totals
	Excellent	Good	Fair	Poor	
Excellent	53	9	3	1	66
Good	11	5	9	0	25
Fair	4	2	4	0	10
Poor	0	0	0	0	0
Totals	68	16	16	1	101

Neurological outcome

All 40 patients with concomitant lumbosacral plexus injuries showed at least some evidence of neurologic recovery during the follow-up time. Of these, 14 patients (35%) had complete neurologic recovery with no motor or sensory deficiencies of the lower legs. All except one of these patients had excellent or good functional results. The only patient with an unsatisfactory functional result had pain in the posterior part of the pelvic ring. Eight patients (20%) had only sensory deficits and their functional results were excellent or good. Partial motor deficits were recognized in 18 patients (45%), and 6 of these patients had chronic radicular pain in the lower leg at the final follow-up.

Prognostic factors of outcome

Most of the patients with an excellent or good radiological result (78/91) had at least a good functional result. There was a significant relationship between the radiological and functional results (Odds ratio 4.0, 95% confidence interval: 1.0 to 16.1). On the other hand, 13 patients with an excellent or good radiological result had a fair or poor functional outcome (**Table 18**). The most significant factor associated with this finding was the occurrence of a symptomatic lumbosacral plexus injury (motor deficiencies), which was observed in 8 of these 13 patients, but only in 11 of the 78 patients who had an excellent or good radiological and functional result (OR 9.2, 95% CI: 2.7-35.3).

An excellent radiological result with displacement ≤ 5 mm showed a clear association to excellent or good functional outcome when single prognostic factors were analysed, and also in the multifactorial analysis (**Table 19**). The presence of neurologic injury after the trauma and also the permanent neurologic injury showed an association with unsatisfactory functional outcome (**Table 19**). Female gender and age (< 33 years) were also prognostic factors. On the other hand, the fracture type (C1, C2 or C3) and ISS failed to show any association with functional recovery. Uro-

logic deficiencies (n=5) and sexual deficiencies (n=5) were associated with severe sacral plexus injuries in 6 of 9 patients.

Table 19. Analysis of prognostic factors associated with the functional outcome after operative treatment of type C pelvic fractures in a series of 101 patients.

	Functional outcome		Crude odds ratio		Adjusted odds ratio [a]	
	Excellent/Good	Fair/Poor	OR	95% CI	OR	95% CI
Age						
≤33	54 (0.9)	4 (0.1)	5.9	1.8-20 [b]	5.3	1.4-20 [b]
≥34	30 (0.7)	13 (0.3)				
Gender						
Female	33 (0.9)	2 (0.1)	4.9	1.0-23 [b]	8.8	1.6-50 [b]
Male	51 (0.8)	15 (0.2)				
Primary lumbosacral nerve injury						
Yes	32 (0.7)	11 (0.3)	3.0	1.0-8.8 [b]		
No	52 (0.9)	6 (0.1)				
Permanent lumbosacral nerve injury						
Yes	17 (0.7)	9 (0.3)	4.4	1.5-13 [b]		
No	67 (0.9)	8 (0.1)				
Radiologic result						
Excellent	62 (0.9)	4 (0.1)	9.2	2.7-31 [b]	9.3	2.4-36 [b]
Good/Fair	22 (0.6)	13 (0.4)				

Figures within parentheses are rates.

[a] Only factors showing a possible association with the functional outcome when analysed as single factors, were included and reported in the multifactorial analysis.

[b] Statistically significant observation

Complications

Eight patients had loss of reduction after internal fixation. In 6 patients this occurred in the posterior pelvic ring injury and 5 of these had reoperation. In all 5 patients, a clear radiological correction was achieved and the final functional result was excellent or good in 4 of 5 patients. In 2 patients, loss of reduction occurred in the rami fracture site, one after intramedullary screw fixation, and the other after plate osteosynthesis. Both these redisplacements were treated non-operatively. Two deep SSIs were noted; one after a severe open fracture and the other followed a closed degloving soft tissue injury on the sacrum. Both SSIs were treated with surcical revision with an excellent or good final functional outcome. Three patients had superficial wound infections which were treated non-operatively. One L5 nerve root lesion developed after iliosacral-screw penetration of the anterior superior surface of the sacrum.

5.4. Prognostic factors of outcome after lumbopelvic fixation of spinopelvic dissociations

According to the Roy-Camille classification, 15 patients had type 2 and 21 patients type 3 transverse sacral fracture. Based on the modified classification system (**Fig. 3**), there were 6 type 2a, 9 type 2b, 14 type 3a, and 7 type 3b transverse sacral fractures. No Roy-Camille type 1 or burst fractures of S1 (Strange-Vognsen and Lebech 1991) were observed. The transverse sacral fracture in the Roy-Camille type 2 fractures was at S2 level in 11 of 15 cases (73%), whereas the Roy-Camille type 3 transverse fractures were between the S1 and S2 vertebral bodies in 14 of 21 cases (67%) (**Table 20**). Four patients had segmental sacral fractures. Sixteen patients (44%) had complete translational displacement in the transverse sacral fracture in either a ventral (type 2) or dorsal (type 3) direction. A concomitant anterior pelvic ring injury was observed in 28 patients (78%).

Table 20. Anatomical characteristics of Roy-Camille type 2 and 3 transverse sacral fracture types (n=36).

Fracture type	Patients	Level of transverse sacral fracture				Complete fracture displacement	
Roy-Camille	n	S1-S2	S2	S2-S3	S3		
Type 2	15	1	11 [a]	1	2	9	60%
Type 3	21	14 [a]	5 [a]	2 [a]	0	7	33%
Total	36	15	16	3	2	16	44%

[a] one segmental fracture

Operative treatment

Thirty-three patients were operated within 21 days of injury, with a median time from admission to surgery of 8 days (IQ25-75, 3-12). Three patients (8%) had late reconstructions (26-34 days after the injury) because of delayed diagnosis (n=2) or severe polytrauma (n=1). Twenty-one patients had staged reconstruction consisting of anterior pelvic ring fixation followed by segmental lumbopelvic fixation. The lumbopelvic fixator was removed in 28 patients at an average of 26 (range, 13-66) months post-operatively. Consolidation of the sacral fracture was confirmed with CT prior to removal.

Radiological results

The radiological end results in the vertical sacral fractures and in the anterior pelvic ring injuries were excellent (19 patients, 53%) or good (17 patients, 47%) in all cases. Postoperatively there was no loss of sacral fracture reduction. Kyphosis in the transverse sacral fracture improved from a mean of 38 (range, 0-90) degrees to 22 (range, 0-58) degrees, and the translational displacement improved from a mean of 15 (range, 0-70) mm to 6 (range, 0-25) mm. The average kyphotic deformity in the Roy-Camille type 2 fractures was initially greater and it improved from a mean of 52 (range, 0-90) degrees to 25 (range, 0-45) degrees, whereas in the Roy-Camille type 3 fractures it

improved from a mean of 27 (range, 0-70) degrees to 20 (range, 0-58) degrees. The average translational displacement improved from 19 to 7 mm in the type 2 sacral fractures and from 13 to 5 mm in the type 3 sacral fractures.

Neurological outcome

Sacral plexus injury with motor and/or sensory deficits (usually L5 and S1 nerve roots) in the lower extremities was observed in 35 patients, with cauda equina syndrome affecting 29 patients. One patient had paraplegia resulting from T12 burst fracture, and 6 patients had paraparesis associated with lumbar burst fractures. Unstable spinal fractures were treated surgically. Preoperatively, the neurological injury was graded according to Gibbons classification as grade 4 in 29 cases, grade 3 in 5 cases, grade 2 in one case, and grade 1 in one case. The neurological recovery according to the Gibbons criteria is presented in **Table 21**. At least some neurological recovery was observed in 34 patients with an associated sacral plexus injury. The only patient without any neurological improvement had the T12 burst fracture with associated paraplegia. Seventeen of 29 patients (59%) with a cauda equina injury (Gibbons grade 4) had full recovery of their bladder and bowel functions. Of 36 patients, 7 (19%) underwent a full neurological recovery. Eight patients (22%) were left with sensory deficits, while 9 patients (25%) had motor and sensory deficits in the lower extremities. Twelve patients (33%) had permanent cauda equina deficits (**Table 22**).

Table 21. Improvement in the Gibbons score from pre-operative to final follow-up in transverse sacral fractures with partial or complete translational displacement (n=36).

Degree of translational displacement	Improvement in Gibbons Score			
in transverse sacral fracture [a]	3	2	1	0
Partial	2	7	6	5
Complete	2	1	2	11

[a] p=0.038

Table 22. Neurological recovery after treating spinopelvic dissociations with lumbopelvic fixation and neural decompression (n=36).

Final neurological status	Patients	
Full recovery	7	20 %
Sensory deficits in the lower extremities	8	22 %
Motor and sensory deficits in the lower extremities	9	25 %
Permanent bladder and/or bowel dysfunction	12	33 %

Prognostic factors of outcome

Roy-Camille fracture classification (type 2 vs. type 3) did not correlate with neurological recovery (as defined as a change in Gibbons score, p = 0.672) nor with final clinical outcome (POS clinical score, p = 0.607). However, the degree of initial translational displacement in the transverse sacral fracture had a statistically significant influence on neurological (**Table 21**) and clinical outcome. Complete translational displacement of the transverse sacral fracture was associated with poor clinical outcome (POS Clinical Score of 1-2) (p <0.001). This association was also seen when patients with paraplegia or paraparesis (n=7) due to associated thoracolumbar fractures were excluded (p=0.01) (**Table 23**). In patients with only partial translational displacement in the transverse sacral fracture, 85% had good clinical outcomes, whereas patients with a complete translational displacement, 75% had a poor clinical outcome (**Table 23**).

Table 23. Comparison between patients with and without paraparesis in the correlation between outcome, based on the POS clinical score, and the degree of translational displacement in the transverse sacral fracture (n=36).

Degree of translational displacement in transverse sacral fracture	POS Clinical Score (1-4 points)			
	All patients, n=36 [a]		Pts without paraparesis, n=29 [b]	
	Good (3-4)	Poor (1-2)	Good (3-4)	Poor (1-2)
Partial	17	3	15	3
Complete	4	12	4	7

[a] p < 0,001

[b] p = 0,01

In the 15 patients with flexion type sacral fractures (type 2a and 2b), there was no significant association between fracture characteristics and outcome (p=1.00). In the 21 patients with extension type sacral fractures (type 3a and 3b), the degree of initial translational displacement in the transverse sacral fracture was associated with clinical outcome (p = 0.013). Poor clinical outcome was seen in 6 of 7 patients with completely displaced sacral fracture (type 3b) and in only 4 of 14 patients with partial sacral fracture displacement (type 3a).

In 15 of 20 patients (75%) with partial translational fracture displacement, the Gibbons score improved from the preoperative examination to the final follow-up (**Table 21**). The Gibbons score improved only in 5 of 16 patients (31%) with complete translational fracture displacement (**Table 21**). The difference in the improvement between these groups was statistically significant (p = 0.038). The average Gibbons score improved from 3.7 to 2.7 during the follow-up period. One patient with partial fracture displacement had a Gibbons score of 1 pre-operatively. None of the patients showed deterioration in their pre-operative Gibbons score compared with their last follow-up score.

The quality of pelvic fracture reduction influenced the outcome. There was a statistically significant (p = 0.048) association between an excellent radiological result in the vertical sacral fractures and a good POS clinical score (**Table 24**). In 19 patients with excellent radiological results (fracture displacement ≤ 5 mm), 74% had a good clinical outcome, whereas 59% of 17 patients with a good radiological result (displacement 6-10 mm) had a poor clinical outcome. In addition, post-operative AP displacement in the transverse sacral fracture was associated with POS clinical score (p=0.011) (**Table 25**). The mean (±SD) values in AP displacement were 4 (±3) mm and 9 (±7) mm in patients with good and poor POS clinical scores, respectively. Also, the post-operative kyphosis was associated with POS clinical score (p=0.018) (**Table 25)**. The mean (±SD) kyphosis in the transverse sacral fractures was 17° (±10°) and 29° (±15°) in patients with good and poor POS clinical scores, respectively.

Table 24. Correlation between the radiological end results in vertical sacral fractures and treatment outcome, based on the POS clinical score, after operative treatment of spinopelvic dissociations (n=36).

Radiological end result in vertical sacral fractures [a]	POS Clinical Score (1-4 points)	
	Good outcome (3-4 points)	Poor outcome (1-2 points)
Excellent (displacement 0-5 mm)	14	5
Good (displacement 6-10 mm)	7	10

[a] p = 0,048

Table 25. Correlation between post-operative AP displacement and kyphosis in transverse sacral fractures and treatment outcome, based on the POS clinical score, after operative treatment of spinopelvic dissociations (n=36).

Radiological end result in transverse sacral fractures	POS Clinical Score (1-4 points)	
	Good outcome (3-4 points)	Poor outcome (1-2 points)
AP displacement (mean ±SD) [a]	4 (±3) mm	9 (±7) mm
Kyphosis (mean ±SD) [b]	17 (±10) degrees	29 (±15) degrees

[a] p = 0.011
[b] p = 0.018

None of the other parameters evaluated had a statistically significant association with neurological recovery or final clinical outcome.

Complications

Drawbacks related to the operative treatment with lumbopelvic fixation were rare. One delayed union occurred unilaterally in the vertical sacral fracture requiring two further surgeries; a change of longitudinal rods and bone grafting. No deep SSI was noted. Two patients with an open sacral fracture, developed superficial wound infections that were treated with wound debridement and antibiotics without further complications. Twelve patients had late breakage (fatigue fracture) of components of the lumbopelvic fixator without any effect on the end radiological or clinical results.

6. DISCUSSION

High-energy pelvic fractures continue to present a serious challenge to trauma care. This study was initiated to investigate the outcomes of acute, life-saving, and definitive management of unstable pelvic ring injuries in patients admitted from 1982 through 2011 to a level I trauma centre.

Over the last four decades, our knowledge has increased on the assessment, trauma mechanisms, classification, and management protocols for this particular, potentially lethal injury. During the 1970s, the patho-anatomical pattern of a lethal vascular injury was revealed in post-mortem studies (Huittinen and Slätis 1973). At the same time, the first case report was published on the use of TAE in the emergency treatment of pelvic fracture-related arterial bleeding (Margolies et al. 1972). Later, larger clinical series were published on the use of the TAE technique, and they showed an overall mortality rate of 36 to 50% (Matalon et al. 1979, Mucha and Farnell 1984, Panetta et al. 1985, O'Neill et al. 1996). The use of TAE was initiated in our institution in 1996, and since that time, it has been incorporated into the treatment protocols of our institution.

After the wide adoption and successful outcomes of external skeletal fixation devices for the treatment of extremity injuries, interest was focused on the use of these devices in pelvic fracture management (Carabalona et al. 1973, Slätis and Karaharju 1975). These devices were shown to facilitate recovery more effectively than bed rest or a pelvic sling, with or without traction (Slätis and Huittinen 1972, Slätis and Karaharju 1979). Later studies showed that the external fixators had limitations for definitive management of grossly unstable type C pelvic injuries (Tile 1988, Kellam 1989, Tile 1995).

In the 1980s, the concept of internal fixation was introduced, for both anterior and posterior aspects of the pelvis. Based on previous biomechanical studies (Leighton et al. 1991, Tile 1995), the approaches included plating the SP and stabilizing the sacroiliac complex with screws or plates (Goldstein et al. 1986, Kellam at al. 1987, Ward et al. 1987, Matta and Saucedo 1989). However, rami fractures were considered less important, and they were stabilized only sporadically, even though it had been shown that the anterior arch was important for the overall stiffness of the pelvic ring. Therefore, the concept of plate fixation for treating displaced pubic rami fractures was initiated in our institution. We used a new anterior extraperitoneal approach (Hirvensalo et al. 1993). In addition, since the early 1990s, a less-invasive posterior approach has been used for open reduction and iliosacral screw fixation of sacral fractures.

Management of H-shaped sacral fractures with spinopelvic dissociation was an especially difficult challenge in the 1990s, because there were no general guidelines or treatment protocols for these rare injuries. The open reduction with segmental lumbopelvic fixation technique described in this study was developed in our institution, and it has since become incorporated into our institutional protocols. This operative technique was initially based on the implementation of new spinal transpedicular fixation devices and the Galveston technique for iliac screw placement (Allen and Ferguson 1982).

6.1. Anterior external fixation frame in pelvic fracture management

This study aimed to evaluate of the use of a trapezoid compression external fixation frame in patients with type B and C pelvic ring injuries, both in terms of biomechanics (fracture reduction and loss of reduction) and clinical efficacy (patient outcome). The results showed that a trapezoid anterior external frame is not optimal for stabilizing a vertically unstable pelvis (type C injury), and there is a high likelihood of hemipelvis migration. Similarly, an anterior trapezoid frame alone cannot reliably stabilize a rotationally unstable pelvis with disruption and widening of the SP (type B open book injury). On the other hand, an internally rotated hemipelvis with displaced pubic rami fractures (type B lateral compression injury) is relatively stable, and this injury can be stabilized adequately with an anterior external frame, when indicated, but compression should be avoided during a closed reduction and application of the fixator.

The non-operative modalities of treatment, including prolonged bed rest with or without traction, do not permit patient ambulation. Early application of an anterior trapezoid frame prevents undesirable movement at the site of the fracture, thus, patients have reported marked diminution in the severity of fracture pain (Karaharju and Slätis 1979, Slätis and Karaharju 1980). This approach facilitates nursing activities for the patient, and it also avoids the discomfort of traction. The frame must remain in place for at least 6 weeks, and it may complicate the patient's life in many respects. The present study showed that the trapezoid frame failed to provide sufficient vertical stability to permit early transfer from the bed to a chair and any weight-bearing ambulation in type C pelvic ring injuries.

It is difficult to perform a closed reduction of a severely displaced type C pelvic ring injury. An autopsy examination study of patients that had sustained multiple traumas showed that anatomical reduction of a posterior fracture-dislocation by external manipulation was impossible in the majority of cadaver pelvises, because either ligamentous or osseous tissues, or both, could interpose into the SI-joint, and the hemipelvis had undergone triplane displacement (Bucholz 1981). The finding that a closed reduction was imperfect was not surprising, because the manipulation of fragments with a closed approach seldom allows anatomical reduction, particularly when pins must be placed at a distance from the fracture site. Even with open reduction techniques, a perfect reduction might be difficult to achieve. The present study showed that, in 95% of patients, the primary reduction worsened during the period that external fixation was maintained for treating type C pelvic injuries. In addition, these patients had malunions with fracture displacements greater than 10 mm at the end of follow-up. Only 7.5% of patients with type C pelvic fractures achieved pain-free outcomes.

Technically, it is considered relatively easy to manage type B open book injuries with closed reduction and external fixation. In this study, open book injuries were rare. For most of the eight patients with open book injuries, radiological results showed a marked vertical displacement or diastasis in the symphysis at the end of follow-up. The vertical displacement in the symphysis resulted in an unsatisfactory functional outcome for the patient. Bircher (1996) reported that, when using an external fixation frame to stabilize an open book injury, there is often some loss of reduction during

the first week after mobilization, and this loss is a reflection of severe ligamentous damage to the pelvic floor and anterior SI-joint. This type of advanced injury allows some rotation of the hemipelvis in an upward direction and also leads to vertical dislocation in the symphysis; however, these movements are not equivalent to true vertical instability (Bircher 1996). Interestingly, the site of the pain was most frequently in the back, not in the symphyseal area, which indicated that the injury pattern in the sacroiliac region was more substantial than the radiographs could reveal. Biomechanical testing of open book injuries has shown that external fixators cannot achieve the stability provided by internal fixation (Tile 1995). In addition, among the different external frame configurations available, none provide any significant advantages over the others (Bell et al. 1988, Tile 1995, Ponsen et al. 2003). The best stability can be achieved by placing one or two plates over the symphysis (Tile 1995).

Type B lateral compression injuries are relatively stable injuries; they do not cause an increase in pelvic volume. In the present study, this was the most frequent injury type. In the first weeks after treatment, re-displacement of the fragment was observed in two-thirds of the patients. This showed that the trapezoid external fixation device was also suboptimal for stabilizing the injury in this subgroup. In eight patients, the displacement after closed reduction was worse than the displacement observed in the initial fracture. This result can be explained by a poor reduction technique, which caused unnecessary compression into the ring. Reduction requires external rotation, and the hemipelvis is maintained in external rotation with an anterior external frame (Tile and Pennal 1980). Poor radiological results correlated with poor functional results. More than 10 mm of vertical displacement and shortening at the site of a ramus fracture comprised a poor prognostic sign. These patients reported pain significantly more frequently and they showed worse functional results than patients with better radiological results.

Neurological deficiencies were present in 40% of type C injuries, but in only 10% of type B injuries. These findings agreed with earlier studies (Tile 1995, Tornetta and Matta 1996). Higher incidences have also been reported (Huittinen and Slätis 1972). In a study on the outcome of 58 patients with type B or C pelvic fractures, Pohlemann et al. (1994) reported sensory deficits in 21% of patients with type B injuries and motor or sensory deficits in 60% of patients with type C injuries after an average 2.2-year follow-up. The incidence of associated lumbosacral plexus injuries depends on the injury pattern in the posterior part of the pelvic ring (Denis et al. 1988). In the present study, neurologic injury was more common in sacral fractures (41%) and in sacroiliac dislocations or fracture dislocations (57%) than in transiliac fractures (17%).

The degree of instability of the pelvic ring influences the outcome. Type B injuries have a better prognosis than type C injuries (Dujardin et al. 1998, Dźupa et al. 2011). After treatment, long-term sequelae, such as chronic pain, are less frequently observed in rotationally unstable type B injuries than in completely unstable type C injuries (Tile 1988, Pohlemann et al. 1994). Pohlemann et al. (1994) showed that this difference was mainly related to a residual posterior displacement greater than 5 mm and neurological deficits. Semba et al. (1983) evaluated 30 conservatively treated Malgaigne fractures and found that a combined initial anterior and posterior displacement greater than 10 mm led to a markedly higher frequency of severe low back pain, compared to smaller combined

initial displacements. McLaren et al. (1990) found that both pain and functional results were significantly worse in a group with more than 10 mm of displacement in the posterior pelvic ring. In the present study, more than 10 mm of residual vertical displacement in an injury to the posterior pelvic ring was a poor prognostic sign. Matta and Tornetta (1996) stated that 10 mm is an acceptable reduction for treating an injury to the posterior pelvic ring, but they also reported that reductions of posterior injuries to within 4 mm did not reduce posterior pain more than reductions between 5 and 10 mm.

Pohlemann et al. (1996) reviewed 28 patients with type B injuries and 30 patients with type C injuries treated either with an external fixator or with open reduction and internal fixation. They found a significant difference in clinical outcome for type B and type C injuries, measured with the POS clinical score. The clinical results showed a poor outcome in 11% of patients with type B injuries and in 50% with type C injuries. That study also showed that anatomical restoration of the pelvic ring was correlated with a higher probability of a good clinical result; however, even when this criterion was met, 20% had only fair clinical results. In the present analysis of type C injuries treated with a trapezoid external frame, we found that, in 33 out of 34 patients, an unsatisfactory functional result was partly or totally caused by inadequate reduction and stabilization of the fracture. In addition, 14 patients in this group had a permanent neurologic injury that influenced the final outcome.

Based on the results from this study and those reported in the literature, it can be concluded that clinical applications of anterior pelvic external fixators comprise the resuscitation phase, initial fracture stabilization phase, and sometimes, in complex injuries (type C), the definitive phase for fixation of the anterior part of the pelvic ring, in conjunction with posterior internal fixation. Open book injuries are the most severe of the type B injuries, because they carry a potential risk of permanent disability. An anterior external frame is of limited value in the definitive treatment of open book injuries. Type B lateral compression injuries are relatively stable injuries, and therefore, it is usually unnecessary to use external fixators in minimally-displaced lateral compression injuries. In patients with multiple injuries, an external frame in the early phase may be indicated to relieve pain and facilitate nursing care.

6.2. The role of TAE in acute treatment of major pelvic hemorrhage

The rapid assessment and control of massive arterial bleeding associated with pelvic injuries secondary to blunt trauma pose a challenge for emergency trauma care. Exsanguinating bleeding has been identified as the major cause of early death in multiple-trauma patients with pelvic ring injuries (Rothenberger et al. 1978, Gilliland et al. 1982, Cryer et al. 1988, Holstein et al. 2012). In the present study, the maximum size of the bleeding pelvic artery and the bleeding vessel score were associated with increased mortality. The prognosis was worse for patients bleeding from the internal iliac artery or the external iliac artery (mortality 57%) compared to patients bleeding from more distal, smaller pelvic arteries (mortality 24%).

TAE should be considered without delay in patients with pelvic fractures that remain hemodynamically unstable, despite adequate resuscitation and provisional stabilization of the pelvic ring. The worst prognosis is related to exsanguinating bleeding from the large pelvic arteries or from multiple smaller arteries. The total length of stay in the angiography suite was nearly 3 h, on average. Although we could not determine any differences between survivors and non-survivors in the length of stay in the angiography suite, 3 hours is a long period of time for the bleeding control procedure in patients that are exsanguinating in extremis. Therefore, in critical situations, it is reasonable to use non-selective embolization by promptly occluding the main trunk of the internal iliac artery, either uni- or bilaterally. This procedure is considered time-saving and effective compared to selective embolization of more distal, smaller arteries or multiple arteries. On the other hand, selective embolization is preferable in patients that respond to initial shock therapy, and exhibit extravasation from a single arterial branch.

Direct pelvic packing via a retroperitoneal approach has been proposed as a damage control treatment for patients that are exsanguinating, but are not in an adequate condition for transport to the angiography suite (Ertel et al. 2000, Ertel et al. 2001, Tötterman et al. 2007, Osborn et al. 2009, Papakostidis and Giannoudis 2009). In these rare cases, when the patient is in extremis, pelvic packing may slow down the bleeding sufficiently to gain time for resuscitating the patient to a status suitable for tolerating the definitive arterial bleeding control provided with TAE (Tötterman et al. 2007, Gaarder et al. 2008, Osborn et al.2009, Suzuki et al. 2009a). Pelvic packing and TAE play complementary roles in the control of massive intrapelvic bleeding (Cothren et al. 2007, Tötterman et al. 2007). In a systematic review of pelvic packing studies, Papakostidis and Giannoudis (2009) concluded that this procedure can facilitate early control of intrapelvic bleeding and provide crucial time for more selective management of hemorrhage with embolization.

The source of arterial bleeding is verified with angiography. Bleeding can be occluded definitively with embolization. Contrast-enhanced trauma CT might detect active arterial bleeding, but not all instances require invasive intervention (Diamond et al. 2009), and conversely, the absence of a contrast blush on a trauma CT scan does not rule out active arterial bleeding (Brown et al. 2005). All imaging techniques for detecting the arterial source of bleeding are time-consuming. A precise assessment and control of exsanguinating bleeding from large pelvic arteries, like the internal iliac artery, requires time. This time can be gained partly by applying EPP, and partly by temporarily occluding the aorta with a left side resuscitative thoracotomy and aortic cross-clamping. This procedure has been incorporated into clinical guidelines, but survival is rare (White et al. 2011). More recently, resuscitative endovascular balloon occlusion of the aorta (REBOA) has been accepted as the preferred initial manoeuvre for controlling massive pelvic hemorrhage (Stannard et al. 2011, White et al. 2011).

Arterial bleeding may occur from any branch of the internal or external iliac system. In the present study, 86% of patients exhibited bleeding from the main trunk or main branches of the internal iliac artery, 4% from the main trunk or main branch of the external iliac artery, and 10% from both the internal and external iliac systems. Angiography revealed multiple bleeding vessels in two-thirds of the cohort and bilateral arterial bleeding in one-third of the cohort. Similar incidences were reported

by O'Neill et al. (1996). A higher incidence of bilateral bleeding (64%) was reported in a post-mortem angiography study by Huittinen and Slätis (1973) on individuals that sustained pelvic fractures in accidents. In the present study, all bleeding from the internal iliac arteries and from the smaller pelvic arteries were treated successfully with embolization, and no rebleeding was detected from the occluded vessels. Due to the extensive collateral circulation in the pelvis, even the main internal iliac artery can be occluded (Ravitch 1964, Seavers et al. 1964, Chait et al. 1968). The complication rate after emergency uni- or bilateral internal iliac artery embolization is typically low (Travis et al. 2008), as shown in the present study.

Massive bleeding and the worst prognosis are often associated with rupture of the internal iliac artery. Hemorrhage control of a ruptured internal iliac artery might be technically difficult with packing. The internal iliac artery is short, about 4 cm long, and it arises from the common iliac artery, above the pelvic brim (Fig. 2), at the level of the lumbosacral intervertebral disc. From there, it descends to the upper margin of the greater sciatic foramen, where it divides into its main branches (Williams and Warwick 1980). Even when retroperitoneal pelvic packing is considered for reducing internal iliac artery bleeding, it is difficult to achieve a tamponade when the compression swabs are only placed into the true pelvis. In theory, the swabs should also be placed above the pelvic brim, against the trunk of internal iliac artery. However, in that location, the swabs may also cause compression of the external iliac artery, which would increase the risk of critical ischaemia in the lower leg.

Angiography is an effective tool for identifying rare bleeding sources, such as the femoral circumflex artery in the external iliac system. Bleeding from the branches of the external iliac artery can be best controlled with selective angiographic embolization. EPP will not tamponade this more lateral, anterior source of hemorrhage, and direct surgical bleeding control is too difficult without angiographic information about the anatomical location of the bleeding artery. On the other hand, rupture of the main trunk of the external iliac artery is unique, because it is the only arterial injury that requires immediate surgical repair. This arterial injury might be suspected in connection with a crushed pelvis (Huittinen and Slätis 1973). A rupture of the common iliac artery is also possible, but rare. It is also an indication for early surgical repair to restore the arterial supply and avoid critical ischaemia of the lower leg, and subsequent limb loss (Green and Allen 1977, Henry et al. 1997).

Arterial bleeding may occur in all pelvic fracture patterns. In the present study, three-fourths of arterial bleedings (78%) occurred in high-energy type C pelvic ring injuries. The other one-fourth of arterial bleedings were associated with other pelvic ring injuries (type B: 14%; type A: 2%) and with acetabular fractures (6%). In the three acetabular fractures found in our study, the femoral head was displaced centrally, and it was associated with an injury to the anterior column or both columns of the acetabulum. Similar findings, both in the prevalence of acetabular fractures (Töttermann et al. 2006) and fracture morphology (Stephen et al. 1999, Magnussen et al. 2007), were reported in earlier studies on acetabular fracture-related arterial bleeding.

Eleven out of 14 non-survivors in the present study had an unstable, type C pelvic ring injury. This rate is consistent with the finding that all cases of massive bleeding from large pelvic arteries and

84% of cases of bleeding from medium-sized arteries were observed in type C pelvic ring injuries. However, we were not able to find statistically significant differences in the types of pelvic fractures between survivors and non-survivors. This was probably due to the relatively low number of patients in the study, particularly for some fracture types, which could lead to a type II error. A recent trauma registry-based study of 5340 patients with pelvic ring disruptions showed that the mortality rate was higher among patients with type C fractures than among patients with types B and A fractures (Holstein et al. 2012). This result was the same between patients with non-isolated pelvic injuries that had additional injuries in other body regions and patients with isolated pelvic ring injuries.

Identifying patients with major arterial hemorrhage can be difficult; there is currently no emergent parameter or single test available for detecting hemorrhage. Several general risk factors have been found, but none of these parameters is sufficiently specific to identify patients at the highest risk of death (Table 2). In the present study, we found some clinically feasible parameters for identifying non-survivors among patients with massively bleeding blunt pelvic traumas, after excluding patients with fatal head injuries. Based on the BE obtained upon admission (the first recorded BE), we identified a reasonable cut-off value for predicting mortality. Among patients with pelvic arterial bleeding, a BE value less than the cutoff value of -10 mmol/l indicated a 75% chance of death. On the other hand, the specificity for that indicator was relatively low, because among the patients with a BE less than -10 mmol/l, 37.5% survived. Our finding is consistent with a previous study, which showed that a BE less than -10.1 mmol/l could predict mortality with a sensitivity of 33% and specificity of 94% (Starr et al. 2002).

In the present study, we used glue and/or coils to occlude the bleeding arteries, and no rebleeding occurred from embolized vessels. On the other hand, one repeated angiography revealed a new bleeding artery, which was treated with selective embolization. In a study by Shapiro et al. (2005), three of 16 patients (19%) required a repeated TAE, due to ongoing pelvic hemorrhage. However, they did not report the source of rebleeding. In another study, Fang et al. (2009) reported that 18.6% of patients that received embolizations underwent a second TAE. In the second TAE, the sources of bleeding were new sites in 38%, previously embolized sites in 27%, and both of these in 35% of patients. In a study by Gourlay et al. (2005), the corresponding figures were 68%, 18%, and 14%, respectively. One potential explanation for new bleeding arteries is that they were in vasospasm or had thrombosed during the first TAE, and they started to bleed again later. Alternatively, rebleedings might have resulted from the use of gelatin sponges to occlude the vessels; these sponges absorb quickly, but recanalization can occur between 48 h and a few weeks after the embolization (Mucha and Welch 1988, Velmahos et al. 2000).

In a previous study, head injury was the major cause of death in patients that sustained pelvic fractures, with or without injuries to other body regions (Holstein et al. 2012). In that study, the most common general reason for death, not related to a specific body region, was major hemorrhage, and the primary source of lethal bleeding was the pelvis. In the present study, five of 14 non-survivors (36%) died from head injuries. The cause of death in patients with multiple injuries is often multifactorial; therefore, the contribution of major hemorrhage to mortality is difficult to determine (Pa-

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pakostidis and Giannoudis 2009). Among non-survivors in the present study, none died from ongoing pelvic bleeding, but five died from the bleeding-related, irreversible, lethal triad (acidosis, hypothermia, and coagulopathy) within the first 24 hours. In addition, three late deaths were due to prolonged, hypovolaemia-related, multiple organ failure (MOF), and one died from cardiac arrest. In our series, bleeding-related mortality was 16%, after excluding deaths from head injuries. Further studies are needed to investigate the role of new solutions, such as the use of hypotensive resuscitation, and the use of tranexamic acid in resuscitation (Martin and Schreiber 2014) and endovascular techniques (Brenner et al. 2014) for controlling complex bleeding in pelvic trauma.

6.3. Internal fixation of unstable pelvic ring injuries

The stability of the pelvic ring depends mainly on the integrity of the posterior weight-bearing sacroiliac complex. However, biomechanical studies have shown that the best stability in type C injuries can be achieved by internal fixation of both posterior and anterior pelvic ring injuries (Leighton et al. 1991, Tile 1995). Biomechanical testing has also shown that, in type C injuries, fixation of the SP and pubic rami are important for the overall stability of the pelvic ring, because they contribute approximately 40% of the total ring stability (Tile 1995). The results of the current study favoured reduction and internal fixation of symphyseal disruptions and displaced (> 10 mm), unstable pubic rami fractures in conjunction with adequate posterior fixation, to achieve optimal stability of the entire pelvic ring. A recent review study also concluded that fixation of any associated anterior pelvic ring injury is essential for improving the fixation stability of the entire pelvic ring (Papakostidis et al. 2009).

In pelvic fracture surgery, soft tissues hinder access, resist reduction, and comprise the major source of trauma and surgery-related complications. In this study, the less invasive, posterior longitudinal approach, with an incision close to the midline was used to perform open reduction on sacral fractures, and simultaneous percutaneous iliosacral screw fixation. This approach proved to be safe; it was associated with only a few soft tissue complications and no deep SSIs. In the 1980s, larger posterior approaches were common; they involve an incision along or lateral to the posterior iliac crest and reflection of the gluteus muscles. That approach was associated with soft tissue complications, such as wound necrosis, and SSIs (Goldstein et al. 1986, Kellam et al. 1987). Later, the rate of deep postoperative infections after posterior surgery varied between 0 and 13% (Matta and Saucedo 1989, Templeman et al. 1996, Moed and Karges 1996, Sagi et al. 2009, Suzuki et al. 2009b). In a recent multicentre study, a posterior approach for treating an unstable posterior pelvic ring injury was associated with a SSI rate of 3.4% (Stover et al. 2012). In that study, all patients were treated with surgical debridement, wound closure, and antibiotics, and there was no need for soft tissue reconstructions. Thus, the recent improvement in soft tissue complications may be attributed to less extensive approaches, appropriate treatment of soft tissue degloving injuries, debridement of necrotic tissue at surgery, and the use of less invasive stabilization techniques (Stover et al. 2012).

Iliosacral screw fixation is the gold standard for fixing sacral fractures (Matta and Saucedo 1989, Tile 1995, Matta and Tornetta 1996, Routt and Simonian 1996b). In the current study, the overall complication rate was low with the use of iliosacral screw fixation. One L5 nerve root injury oc-

curred. The most unstable comminuted sacral fractures are particularly challenging, because it may be difficult to achieve adequate pelvic ring stability with iliosacral screw fixation alone. For example, 6 patients in the present study had secondary displacements after screw fixation. The most severe posterior pelvic injuries require special attention and careful preoperative planning. Triangular osteosynthesis and lumbopelvic fixation for sacral fractures has been shown to be biomechanically superior to other techniques (Schildhauer et al. 2003, Yi and Hak 2012). In this study, five patients with sacral fractures did not receive internal fixation, due to the minimal initial fracture displacement. However, in *2* patients, the posterior injury pattern was evaluated incorrectly, and therefore, internal fixation was not deemed necessary; this incorrect evaluation resulted in worsening the position of the fracture, even though the anterior injury to the pelvic ring was fixed with plates. These results support the use of internal fixation, even in high-energy minimally displaced sacral fractures. Minimally displaced sacral fractures appear to be well-suited to percutaneous fixation techniques with cannulated screws, where the screws are placed under fluoroscopic guidance or with other means of navigation. Accurate reduction of the anterior pelvic disruption is typically necessary before the posterior ring injury can be adequately reduced; the latter reduction can be achieved with closed or open methods.

The anterior extraperitoneal approach described by Hirvensalo et al. (1993), and with more detail in this study, provides good access to the symphysis pubis, the inner surface of the pubic rami, and the quadrilateral surface and anterior column of the acetabulum. With current techniques, there is no need to dissect or separate the inguinal neurovascular structures, in contrast to the ilioinguinal approach, which has been used in pelvic fracture surgery for more than 50 years (Letournel and Judet 1993). The anterior extraperitoneal approach is safe without any serious complications, including deep SSI, major bleeding, and nerve injuries. The anterior approach could be combined with an approach along the iliac crest; this combined approach provides access to every anterior part of the pelvic ring and even the anterior side of the SI-joint. We found this approach to be technically easier and less invasive for the patient than the traditional approach. With this technique, it is highly important to protect the external iliac vein and the obturator vessels and nerve. Based on the present study, this combined approach can be recommended for the stabilization of simultaneous transiliac fractures, sacroiliac dislocations, or fracture dislocations and injuries to the anterior pelvic ring.

In this study, the anterior pelvic ring injuries were mainly stabilized with 3.5-mm reconstruction plates and screws. Fixation with plates can be considered accurate and reliable. Reduction was lost in only 1 of 75 anterior fixations with plates. Matta (1996) also found, in a series of 127 patients, that 72 fixations of the anterior pelvic ring were safe and reliable; he recommended this treatment for symphysis pubis dislocations, but only for the most severe pubic rami fractures. In the current study, in 2 of 16 patients, the position of the initially minimally displaced (< 10 mm) and unfixed fracture of the pubic rami worsened, even though the posterior injury was adequately fixed. Only a few patients in our series received an anterior external fixator or intramedullary screw fixation of the rami in combination with a posterior fixation. In the latter group, one loss of reduction was observed. However, due to the small number of cases, no definite conclusions could be drawn about these methods.

Among type C sacral fractures, SI-joint dislocations, and fracture-dislocations, 40 to 60% of cases exhibit a neurologic injury of varying severity (Huittinen 1972, Huittinen and Slätis 1972, Pohlemann et al. 1994, Tornetta and Matta 1996). In the present study, all 40 patients with an associated nerve root injury showed at least some evidence of recovery from the neurologic deficiencies. Similar results were obtained by Reilly et al. (1996), and Tornetta and Matta (1996). Early realignment and stabilization of the posterior pelvis probably provides the best possible environment for neurological recovery. It can be presumed that recovery of the lumbosacral nerves depends on the amount of initial damage to the nerve roots and also on mechanical factors, such as traction or compression of the neurologic structures imposed by fragments of bone (Denis et al. 1988). For neurologic recovery, it seems essential to achieve accurate fracture reduction, to prevent traction of the injured neural structures by stabilizing the ring, and to decompress the sacral nerve roots with indirect or direct methods. These procedures should be performed urgently, in the primary phase, at the time the neural injury is suspected, and as soon as the patient has been stabilized hemodynamically.

After treating unstable sacral fractures, residual vertical displacement of the posterior pelvic ring is correlated with body pain (Nepola et al. 1999). The amount of displacement is potentially relevant. Better functional results were found with residual posterior displacements less than 5 mm in type C injuries (Dujardin et al. 1998). However, Tornetta and Matta (1996) found no difference in patient-reported pain levels when the posterior displacement was less than 5 mm and when it was 5-10 mm after ORIF. In contrast, an increased rate of urinary complaints was noted when more than 5 mm displacement persisted in the posterior pelvis (Copeland et al. 1997). In the present study, a fracture malunion that resulted from poor reduction or loss of alignment was a statistically significant prognostic factor for an unsatisfactory functional outcome. In contrast, an excellent radiological result with a maximal residual displacement ≤ 5 mm in the posterior or anterior pelvic ring was clearly associated with a better functional outcome. In addition, a permanent lumbosacral plexus injury was correlated with an unsatisfactory functional result. A recent study also showed that patients with less than 5 mm residual displacement had the best functional results, according to the Majeed Score, and that increasing displacements were associated with significantly lower scores (Džupa et al. 2011). Optimal results are expected in patients with a residual posterior displacement of 5 mm or less.

6.4. Management and predictors of outcome for spinopelvic dissociations

This study aimed to explore potential prognostic factors related to the neurological and clinical outcomes following surgical treatments of H-shaped sacral fractures with spinopelvic dissociations. The classification system published by Roy-Camille et al. (1985) describes the direction of displacement in types 2 and 3 transverse sacral fractures, but we did not find any correlation between these fracture characteristics and outcome. Therefore, that classification is not useful for predicting prognosis. However, our results showed that the final outcome of surgical treatments for spinopelvic dissociations was associated with the degree of initial translational displacement that accompanied the transverse sacral fracture. Permanent lumbosacral plexus injuries and cauda equina symptoms with bladder and bowel dysfunctions were more frequent in patients with completely dis-

placed transverse sacral fractures, compared to patients with only partially displaced sacral fractures. Also, the clinical outcome was worse in completely displaced transverse fractures.

An H-shaped sacral fracture refers to bilateral vertical fracture lines associated with a transverse fracture line. This fracture is unstable, because it potentially allows both hemipelves to displace cranially, anteriorly, and rotationally in the sagittal plane (flexion), and also, rotationally in the horizontal plane (internal or external rotation), with respect to the upper central sacral segment and the lumbar spine. The deformity of the entire pelvic ring increases in complexity with the addition of an injury in the anterior pelvic ring. In this study, an injury to the anterior part of the pelvic ring was detected in 78% of patients. This frequency is higher than those observed in previous studies, where anterior injuries were reported in 52 to 67% of patients (Schildhauer et al. 2006, Tan et al. 2012). Triplane displacements and rotational deformities in sacral fractures were corrected simultaneously with an open approach. These corrections required lumbopelvic instrumentation and reduction clamps, hyperextension of the hip joints, and manual traction of both lower extremities, with the patient in the prone position. In patients with a sacral fracture combined with an anterior pelvic injury, a staged reconstruction was performed. A reconstruction of the anterior part of the pelvic ring was performed first; and this was followed by posterior lumbopelvic fixation.

In the current study, all patients received an excellent or good reduction (displacement ≤ 10 mm) in vertical sacral fracture lines and also a clear correction, both in AP translation and in sagittal kyphotic angulation, in transverse sacral fractures. The most important finding was the significant association between the radiological and clinical outcomes. Patients with anatomical or near-anatomical reductions had a better clinical outcome than those with > 5 mm residual displacement in the vertical sacral fracture lines. In addition, both the residual post-operative AP translation and kyphosis of the transverse sacral fracture were smaller in patients with good clinical outcomes than in those with poor outcomes.

Displaced transverse sacral fractures result in cauda equina neurological deficits in 44 to 100% of patients (Schildhauer et al. 2006, Ayoub 2012, Tan et al. 2012). In this study, all the sacral fractures were H-shaped. We found that, in Roy-Camille flexion type 2 injuries, transverse sacral fractures typically extended through the S2 body; however, in extension type 3 injuries, transverse sacral fractures were, on average, located slightly more cranially, between the S1 and S2 bodies. Therefore, injuries in all sacral nerve roots, including the S1 nerve root, are more likely to occur in Roy-Camille type 3 sacral fractures than in the more caudal type 2 sacral fractures. Sacral fractures that only cause injuries to the nerve roots from S2 to S5 (without S1 nerve root involvement) might be overlooked, due to the lack of motor or sensory deficits in the lower leg. Urinary and anal continence and sexual function require at least unilateral preservation of the S2 and S3 nerve roots (Gunterberg 1976). In the present study, cauda equina syndrome was present in 81% of patients. Of these patients, nearly two-thirds experienced full neurological recovery of bladder and bowel functions. On the other hand, one-third had permanent bladder and/or bowel dysfunction. Our analysis showed that the degree of post-operative AP displacement and the degree of post-operative sagittal kyphosis in the transverse sacral fracture were associated with clinical outcome. On average, patients had a

better outcome when the treatment achieved accurate reduction of the sacral fracture and adequate neural decompression of the lumbosacral nerve roots.

H-shaped sacral fractures are difficult to reduce and stabilize, due to the highly unstable caudal sacral segment. These injuries require segmental lumbopelvic fixation (Schildhauer et al. 2006, Jones et al. 2012, Lehmann et al. 2012). Other sacral fracture patterns with spinopelvic dissociations, including U-, Y-, and T-shaped sacral fractures (Robles 2009, Tan et al. 2012), are more stable and less complicated. These injuries can be treated with iliosacral screw fixation (Nork et al. 2001, Hunt et al. 2002), with posterior ilio-iliacal (trans-sacral) plate fixation (Gripnau et al. 2009), or with triangular osteosynthesis (Hunt et al. 2002, Gripnau et al. 2009)

Early realignment of the sacrum, restoration of spinopelvic stability, and decompression of the nerve roots, indirectly or directly, are thought to provide the best possible environment for neurological recovery. However, several days are often required to optimize patient physiological status, after severe blood loss, hemodynamic instability, or severe concomitant injuries, before it is possible to perform definitive surgical treatment for a spinopelvic dissociation (Schildhauer et al. 2006, Gripnau et al. 2009). Schildhauer et al. (2006) reported that they did not find any association between the timing of decompression and the degree of neurological recovery. Similarly, in our study, the timing of lumbopelvic fixation and neurologic decompression was not associated with neurological recovery or clinical outcome. Therefore, definitive surgical treatment should be performed only after the patient is stabilized and when they can tolerate a prolonged operation with a potential for marked peri-operative blood loss. In addition, it may benefit the outcome to delay treatment until an orthopaedic surgeon with sufficient expertise is available.

In the present study, all patients showed some evidence of neurological recovery, except one that had a thoracic spinal fracture and a spinal cord injury. One-third of the patients had permanent bladder and bowel impairment, with no recovery, based on the Gibbons criteria. Consistent with our results, a recent study revealed that almost one-third of patients reported residual bladder and bowel dysfunction (Lehmann et al. 2012). The Gibbons score did not improve in 11 of 16 patients (69%) with complete translational fracture displacements. Those results suggested that a shearing injury had transected the sacral nerve roots. For those patients, sacral laminectomy did not improve the outcome of bladder and bowel function. However, in 5 patients (31%) with complete fracture displacement, the Gibbons score improved, probably due to a less severe neuropraxic type of sacral nerve root injury. In those cases, a sacral laminectomy most likely had a positive influence on recovery. When sacral laminectomy was performed as a standard procedure for all sacral fractures, regardless of the initial degree of fracture displacement, no improvement was observed in the rate of neurological recovery (Schildhauer et al. 2006). Therefore, the sacral laminectomy seemed to be indicated in cases of completely displaced sacral fractures, due to occlusion of the central sacral canal at the level of the transverse sacral fracture. Although it is difficult to evaluate the effect of surgical decompression on neurological recovery, particular attention should be paid to achieving indirect neural decompression by performing a sacral fracture reduction as accurately as possible. Our management protocol has been to perform surgical decompression, irrespective of the initial translational displacement, when a peri-operative true lateral fluoroscopy shows severe narrowing

of the central sacral canal, following fracture reduction and lumbopelvic fixation. Improvement in neurological impairment can be expected after surgical treatment, but it is not clear whether sacral laminectomy improves neurological recovery, compared to indirect decompression with sacral fracture reduction alone (Schildhauer et al. 2006, Ayoub 2012, Tan et al. 2012, Yi and Hak 2012).

Spinopelvic dissociations can be treated with lumbopelvic fixation. This procedure was associated with a low rate of complications in long-term sequelae. No deep SSI with exposure of the hardware was diagnosed. However, two superficial wound infections occurred after open fractures. These infections were treated with local wound therapy and antibiotics. In a study of 19 patients with lumbopelvic fixation and sacral laminectomy, 5 patients (26%) developed wound healing problems (Bellabarba et al. 2006). Three of these were treated with surgical debridement in the operating room, and two were treated with local wound therapy, including hematoma or seroma evacuation. Posterior prominence of the iliac screws relative to the plane of the PSISs should be avoided. Special attention should be paid to placing the longitudinal rods as close as possible to the dorsal surface of the sacrum, and medial to, but not posterior to, the PSIS; the starting points should be medialized and the heads of the iliac screws should be countersunk to avoid soft tissue and wound healing problems.

Segmental lumbopelvic fixation provided sufficient stability for bony union. This procedure was associated with no postoperative loss of sacral fracture reduction. One delayed union occurred in a unilateral vertical transforaminal sacral fracture. Posterolateral arthrodesis was not performed at the lumbosacral junction; this decision most likely led to the relatively high rate of asymptomatic late breakage of the posterior hardware. This result was consistent with the findings by Bellabarba et al. (2006), who reported asymptomatic rod fractures in 31% of patients, even when posterolateral arthrodesis had been performed across the instrumented lumbosacral levels. Lumbopelvic fixation appears to be sufficiently stable without arthrodesis. No neurological injuries related to operative treatment were diagnosed. No patients showed deterioration in the Gibbons score when the preoperative score was compared to the final follow-up score.

These findings indicate that a further categorization of the transverse sacral fracture as either partially displaced or completely displaced would be useful in predicting the prognosis of neurological recovery and clinical outcome, following operative reduction and lumbopelvic fixation. Adding these subcategories into the original Roy-Camille type 2 and type 3 sacral fractures would facilitate treatment and prognosis determinations for patients with a severe H-shaped sacral fracture with spinopelvic dissociation.

6.5. Limitations and strengths of the study

One main issue when evaluating outcomes or comparing different treatment methods for pelvic injuries was to determine an appropriate follow-up time for recording the final results. Majeed et al. (1989) noted that patient function improved over the first 18 months, and then stabilized; in contrast, Kreder (2003) identified a functional plateau between 6 months and 1 year post injury. Therefore, it is imperative that follow-up studies for pelvic ring injuries plan at least one year of follow-

up (Gänsslen and Lindahl 2013). In **Studies I** and **III**, the minimum follow-up time was one year; in **study IV**, it was 18 months; and in **Study II**, it was one month (30-day mortality).

The strengths of the current study include the relatively large number of consecutive patients with pelvic fractures treated either with an anterior external fixation frame as a definitive treatment (**Study I**) or with standardized internal fixation techniques (**Studies III-IV**), at a single level I trauma centre. To our knowledge, **Study I** included the largest cohort among all published studies on series of patients with unstable pelvic fractures treated with external fixation. However, the number of type B open book injuries in this study was relatively low (eight patients); therefore, our results on the outcomes for this type of injury should be interpreted with caution. The follow-up rates were high in all four studies; 83% in **Study I**, 100% in **Study II**, 86% in **Study III**, and 97% in **Study IV**.

The major weakness of **Studies I-IV** was the retrospective nature. In **Study II**, patients were included only when arterial bleeding had been verified with angiography; therefore, the study did not include all patients with hemodynamic instability due to pelvic ring injuries. The relatively low number of patients included in that study may lead to a type II error, which must be kept in mind when interpreting our results. The strength of **Study II** lies in the consistency of the treatment protocol performed for consecutive patients over a long study period (12.5 years), with only one exception; the use of trauma CT started during the early years of the study period. Another strength was the extensive array of factors evaluated as prognostic predictors of outcome (30-day mortality).

It can be difficult to evaluate outcome after an operative treatment for a pelvic ring injury, because neurologic and other concomitant injuries are generally present, and these conditions may affect the final functional recovery. The functional scoring system described by Majeed was modified specifically to evaluate the outcome after a pelvic injury. A good scoring system makes it possible to compare different clinical series and different types of fracture. In the present study, the follow-up outcome evaluations were performed by the same author to avoid inter-observer variations. On the other hand, the functional evaluations were not blinded; the use of an independent evaluator may have provided more objectivity in evaluating the follow-up data (**Study III**). For clinical applications, reporting radiological and functional results separately provides more precise information about the outcome than a single score that combines all the main parameters. One disadvantage of the Majeed score was that neurological impairments, which may have relevant prognostic influence, were not integrated into the score; thus, it exclusively measured the functional component of the outcome. In the future, a validated pelvic outcome score would be helpful for comparing results among different fracture types and treatment protocols.

The design of **Study IV** had inherent limitations. The study population of operatively treated spinopelvic dissociations was rather small for statistical analysis; therefore, our results should be interpreted with caution. One limitation was the inconsistent timing in performing the definitive operative treatment, which varied from 0 to 34 days after the trauma. Among 36 patients, 33 received operative interventions within 12 days of the injury, but the other three had late reconstructions (26 to 34 days after the trauma). Operative reduction, lumbopelvic fixation, and decompres-

sion of the nerve roots should be performed early; however, hemodynamic instability and concomitant injuries to other body regions frequently delay the timing of definitive treatment.

To the best of our knowledge, **Study IV** included the largest cohort among all published studies on a series of consecutive patients with surgically treated H-shaped sacral fractures with spinopelvic dissociation. In addition, the strengths of this study included the consistent use of a single protocol for operative reduction and a single lumbopelvic fixation technique during the long study period (18 years), the extensive array of factors evaluated as prognostic predictors of outcome, and the inclusion of only H-shaped sacral fractures.

6.6. Future aspects of emergency treatment

As the population ages, more older people will require acute treatment due to trauma. The number of osteoporotic pelvic fractures in the older population has increased during the past few decades (Kannus et al. 2000, Tosounidis et al. 2010). Patient age was found to be a risk factor for hemorrhage and mortality in patients that sustain pelvic fractures (Rothenberger et al. 1978, Mucha and Farnell 1984, Ertel et al. 2000, Starr et al. 2002, Henry et al. 2002, Smith et al. 2007, Sharma et al. 2008). However, a recent trauma registry-based study of patients with pelvic fractures did not show any differences in mean age or the age distribution between survivors and non-survivors (Holstein et al. 2012). They explained this with the observation that young patients that sustained high-energy traumas had a higher risk of lethal injures to other body regions than older patients. The elevated risk of hemorrhage in older individuals may be due to the fact that arteriosclerosis is common among older people; this condition may limit the ability of injured vessels to tamponade spontaneously through vasospasm (Hak 2004). Thus, older patients frequently require angiographic embolization for vascular control, even with lower grade pelvic fracture patterns (Henry et al. 2002, Hak 2004). Several comorbidities and the wide use of anticoagulant and antiplatelet medications among older individuals increases the risk of bleeding with a pelvic injury (Berndtson and Coimbra 2014). In the future, we expect a greater need for bleeding control procedures designed for treating older patients.

In the resuscitation phase, immediate identification of the major source of pelvic hemorrhage appears to be impossible with the current methods (Suzuki et al. 2009a). Contrast blush in a CT scan is the only means for detecting arterial bleeding prior to an angiography, but the CT does not reveal relevant arterial bleeding in all cases (Brown et al. 2005). In addition, hemodynamic instability is contraindicative for a trauma CT. The aim of the CT scan is prompt identification of patients with a significant arterial source of bleeding. These patients will benefit most from TAE, when it is performed at the appropriate time, with respect to the assessment and management of other associated injuries (Hak 2004). This situation highlights the necessity for further advances in diagnostics and medical imaging of massive arterial bleeding.

The use of large vessel balloon occlusion for resuscitation, such as REBOA, has increased during the past decade (Brenner et al. 2014). Compared to EPP, endovascular techniques are less invasive,

and they are associated with reduced morbidity. Open surgical exploration of a retroperitoneal hematoma increases the danger of infection (Stock et al. 1980, Tötterman et al. 2007, Papakostidis and Giannoudis 2009, Suzuki et al. 2009a). EPP is a highly invasive approach, and it requires a second procedure for removing the tamponades. In addition, the effectiveness of EPP has not been definitively proven in cases of massive bleeding from the main trunk of the internal iliac artery. Aortic balloon occlusion techniques are likely to appear more frequently in the treatment algorithms for bleeding in patients with pelvic injuries. Before that occurs, it is necessary to treat a large series of patients with pelvic fractures and massive bleeding with REBOA and analyse the results carefully to determine whether the complication rate is lower and patient survival is improved compared to results reported to date from studies that used TAE or EPP followed by TAE.

Successful treatment of a patient with a bleeding pelvic trauma requires a multidisciplinary team approach. The future trauma centre should be equipped with all diagnostic, interventional radiological, and operative facilities to avoid transporting an unstable patient to another location for imaging and management. This type of integrated CT-angiography unit could optimize the use of current resuscitation resources. The latest interventions in resuscitation are guided by the concept of hypotensive resuscitation. They aim to avoid excess administration of crystalloids and treat traumatic coagulopathy with early use of fresh frozen plasma, fibrinogen concentrate, platelets, and tranexamic acid, guided by viscoelastometric devices (ROTEM, TEG) (Spahn et al. 2013). It appears that the best chance at survival can be offered with a multidisciplinary approach, prompt pelvic ring stabilization, resuscitation with new strategies, temporary bleeding control with EPP or REBOA, followed by TAE, and an integrated CT-angiography trauma unit.

6.7. Future aspects of definitive management of pelvic ring injuries

Increasing interest during the last two decades in the anterior intrapelvic approach for the treatment of pelvic fractures has led more institutions to adopt this surgical approach and to develop their own modifications (Cole and Bolhofner 1994, Jakob et al. 2006, Ponsen et al. 2006, Sagi et al. 2010, Kacira et al. 2011). Having been the first institution to describe this approach for the treatment of pelvic ring and acetabular injuries (Hirvensalo et al. 1993), our plan is to review our experience in acetabular fracture surgery and perform a critical analysis of the factors that contribute to possible complications. Although we found a small overall complication rate related to the anterior approach described in this study, the question of contributing factors is important, particularly in acetabular fracture surgery. These potential contributing factors include patient-specific factors, such as age, osteoporosis, sex, BMI, and comorbidities; and surgical factors, such as the accuracy of fracture reduction and stabilization. Each of these factors should be analysed in relation to complications, such as loss of reduction, infection, and the need for revision surgery.

Successful treatment of pelvic fractures remains one of the most challenging clinical problems in the management of patients with blunt traumas. In an attempt to analyse pelvis-related long-term impairments, the Majeed Score, the POS, and other scoring systems have attempted to integrate appropriate parameters. These parameters include a pain analysis (including lower back pain), pel-

vic and hip function, walking analysis, impairment while sitting, and fracture-related, concomitant lesions in the lumbosacral plexus and pelvic urogenital organs (resulting in sexual, bladder, and bowel dysfunctions). Therefore, it is necessary to develop an instrument that provides sufficient information on pelvic treatment outcome. An expert group should focus and agree on parameters that should be integrated into a comprehensive clinical scoring system. Additionally, they should focus on the different strengths of parameters, based on their clinical importance.

There is a wide range of completely different types of pelvic ring injury and different treatment concepts are used to treat those injuries. We recommend that future evaluations of long-term results after pelvic ring injuries should be conducted in prospective, multicentre outcome studies that apply a standardized treatment concept and an integrated, standardized outcome parameter analysis. A detailed outcome analysis should focus on results for specific fracture types and on the type of osteosynthesis applied.

7. CONCLUSIONS

On the basis of the present series of studies, the following conclusions can be made:

1.   An anterior trapezoid compression external fixator is not optimal for stabilizing a vertically un-stable pelvis (type C injury), and there is a high likelihood of hemipelvis migration. Similarly, an external frame alone cannot reliably stabilize a rotationally unstable pelvis with disruption and widening of the symphysis pubis (type B open book injury).

2.   An internally rotated hemipelvis with displaced pubic rami fractures (type B lateral compression injury) is relatively stable, and this injury can be stabilized adequately with an anterior external frame, when indicated, but compression should be avoided during a closed reduction and application of the fixator.

3.   The most severe pelvic arterial bleeding is related to the trunk of the internal iliac artery or its main branches due to a high-energy type C pelvic ring fracture. The worst prognosis is related to exsanguinating bleeding from the main trunk of the internal or external iliac arteries (large pelvic arteries) or from multiple branches of the internal or external iliac systems (high vessel size score).

4.   TAE is a reliable method for controlling arterial source of pelvic bleeding with a low rate of complications. In massive hemorrhage with several bleeding arteries uni- or bilaterally, it is reasonable to use non-selective embolization by promptly occluding the main trunk of the internal iliac artery, either uni- or bilaterally.

5.   In critical situations, a damage control protocol may include temporary extraperitoneal pelvic packing or resuscitative endovascular baloon occlusion of the aorta to achieve early hemorrhage control and provide time for a more selective embolization approach to the bleeding. A multidisciplinary approach provides the best chance of survival.

6.   Type C pelvic ring injuries require surgical stabilization. Internal fixation of all injuries in the anterior and posterior pelvic ring provides superior stability for the whole pelvis and better anatomical results as determined by the quality of reduction and lower malunion rate.

7.   In type C injuries, an anatomical or near-anatomical reduction (displacement ≤ 5 mm) is more often associated with a good functional outcome and therefore that should be the goal of operative treatment. However, the prognosis is also often dependent on associated injuries, particularly a permanent lumbosacral plexus injury. Conversely, it is unusual to obtain a satisfactory functional result in the presence of a fair or poor fracture reduction.

8. H-shaped sacral fracture with spinopelvic dissociation is a rare injury pattern. Segmental lumbopelvic fixation is a reliable treatment method for these injuries and it provides sufficient stability for fracture union with a low rate of complications and long-term sequelae.

9. H-shaped sacral fractures with spinopelvic dissociation are associated with neurologic impairment in nearly all cases. The Roy-Camille classification of these fractures (1985) is not prognostic of neurological impairment after operative treatment. Neurological recovery and clinical outcome are associated with the degree of initial translational displacement of the transverse sacral fracture. Permanent neurological deficits are more frequent and the clinical outcome worst in completely displaced transverse sacral fractures.

10. In spinopelvic dissociations, quality of reduction in terms of residual postoperative vertical and AP displacements in the vertical sacral fracture lines and translational displacement and kyphosis in the transverse sacral fracture, is associated with the clinical outcome. Accurate reduction of all sacral fracture components is associated with better clinical outcome.

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