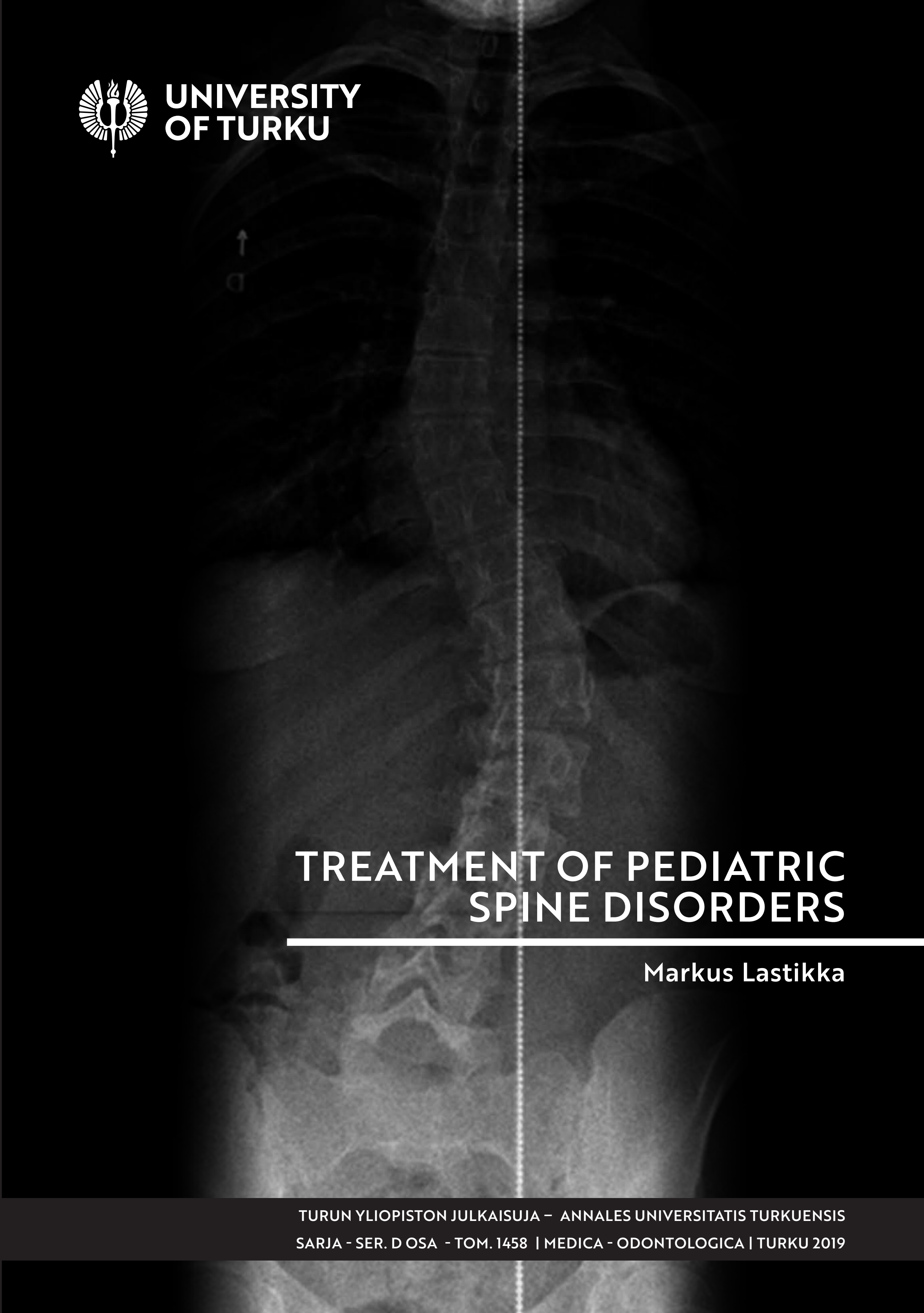

UNIVERSITY OF TURKU

TREATMENT OF PEDIATRIC SPINE DISORDERS

Markus Lastikka

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA - SER. D OSA - TOM. 1458 | MEDICA - ODONTOLOGICA | TURKU 2019

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University of Turku

Faculty of Medicine
Department of Paediatric Surgery
Doctoral program in Clinical Research

Supervised by

Professor Ilkka Helenius, MD, PhD
Department of Paediatric Surgery
Turku University hospital and University of Turku, Finland

Reviewed by

Adjunct Professor
Kari Vanamo, MD, PhD
Department of Pediatric Surgery
Kuopio University Hospital and University of Kuopio, Finland

Professor Ville Leinonen, MD, PhD
Department of Neurosurgery
Oulu University Hospital and University of Oulu, Finland

Opponent

Adjunct Professor Juha-Jaakko Sinikumpu, MD, PhD
Department of Pediatric Surgery Oulu University Hospital and University of Oulu, Finland

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ABSTRACT

Idiopathic scoliosis treatment options include bracing and surgery. Bracing results however depend on the amount of brace wear time, i.e. compliance. To improve compliance a night-time brace has been developed. Because of the great growth potential of the spine in juvenile idiopathic scoliosis (JIS) the right length of the fusion remains unknown. In adolescent idiopathic scoliosis (AIS) it is not yet established which is the best rod alternative. Surgery of the cervical spine is rare and complicated.

The goals of this thesis were to study: (1) which brace treatment is more effective in main thoracic AIS, a night-time or full-time brace (Study I)? (2) Does posterior spinal fusion extended to the stable vertebra provide similar outcome in JIS patients compared with AIS patients with fusion to the last central sacral line touched vertebra (Study II)? (3) Which is the optimal rod alternative in deformity correction in adolescents operated for idiopathic scoliosis (Study III)? (4) To review the indications and outcomes of instrumented cervical spinal fusion in children (Study IV).

This thesis is comprised of four retrospective series of paediatric spine patients.

In this study, the Providence night-time brace was as effective in the conservative treatment of main thoracic AIS as the Boston full-time brace. Posterior spinal fusion extended to the stable vertebra provides similar outcomes in JIS patients compared with AIS with fusion to the touched vertebra. Both circular and sagittal reinforced 6.0mm Cobalt-Chromium rods provide adequate coronal correction for adolescents operated for idiopathic scoliosis. The use of sagittal reinforced rods provides better thoracic kyphosis restoration. Skeletal dysplasia associated cervical instability and cervical spine injuries represented the most common indications for instrumented cervical spinal fusion in children. Occipitocervical (OC) spinal fusion and spinal fusion before the age of ten years are associated with higher risk of surgical complications and increased mortality than non-OC fusions and cervical spinal fusions at an older age.

KEYWORDS: Scoliosis, paediatric spine, brace-treatment, spinal fusion.

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TIIVISTELMÄ

Idiopaattinen skolioosin hoitomuotoihin kuuluu korsetti sekä leikkaushoito. Johtuen suuresta jäljellä olevasta kasvusta juveniili idiopaattinen skolioosi (JIS) -potilailla luudutuksen oikeaa pituutta ei tiedetä. Hypokyfoosi (HK) on AIS-potilailla tavallinen. Vielä ei ole vakiintunut mikä on paras tanko vaihtoehto nuoruusiän idioppaattinen skolioosi (AIS) potilailla. Lapsen kaularangan Leikkaushoitoa tarvitaan harvoin ja sitä vaikeuttavat pienet ja hauraat luiset selkärangan rakenteet.

Väitöskirjan tavoite oli tutkia: (1) kumpi on tehokkaampi hoitomuoto rintarangan idiopaattisen skolioosin hoidoksi, yökorsetti vai ympäri vuorokauden pidettävä korsetti (Tutkimus I)? (2) Saavutetaanko stabiiliin nikamaan saakka pedikkeliruuvein tehtävällä luudutuksella JIS-potilailla sama hoitotulos kuin luudutukseen keskisakraalilinjaa koskettavaan nikamaan asti nuoruusiän idiopaattinen skolioosi (AIS) -potilailla (Tutkimus II)? (3) Mikä on paras tankovaihtoehto idiopaattisen skolioosin takia leikatuilla nuorilla (Tutkimus III)? (4) Tutkia lasten kaularangan luudutusleikkauksien syitä ja tuloksia, erityisesti kaularangan ja kallon (OC) luudutusten sekä alle 10-vuotiaina leikattujen osalta (tutkimus IV).

Tässä tutkimuksessa Providence-yökorsetti oli yhtä tehokas hoito kuin Boston-tyyppinen ympärivuorokautinen korsetti rintarangan idiopaattista skolioosia sairastavilla potilailla. Selkärangan luudutus stabiiliin nikamaan JIS-potilailla antoi saman lopputuloksen kuin luudutus keskisakraalilinjaan koskettavaan nikamaan AIS-potilailla. Sekä pyöreät että sivulta vahvistetut 6,0 mm:n koboltti-kromitangot antavat riittävän etusuunnan korjauksen idiopaattisen skolioosin vuoksi leikatuille nuorille. Sivulta vahvistettujen tankojen käyttö paransi rintarangan kyfoosin korjausta ja vähensi riskiä rintarangan hypokyfoosille. Luun kasvuhäiriöiden aiheuttama kaularangan epävakaus ja kaularangan vammat ovat yleisimpiä syitä lasten instrumentoiduille kaularangan luudutusleikkauksille. OC-luudutuksiin ja ennen kymmentä ikävuotta tehtyihin selkärangan luudutuksiin liittyi kohonnut kirurgisten komplikaatioiden ja kuoleman riski alempiin kaularangan luudutuksiin ja vanhemmalla iällä tehtäviin luudutusleikkauksiin verrattuna.

AVAINSANAT: skolioosi, lapsen selkäranka, korsetti hoito, selkärangan luudutus.

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Abbreviations

AIS	Adolescent idiopathic scoliosis
CoCr	Cobalt Chromium
CDH	Cotrel–Dubousset Horizon
FU	Follow-up
HRQoL	Health-related-quality-of-life
h	Hours
HK	Hypokyphosis
JOA	Japanese Orthopedic Association
JIS	Juvenile idiopathic scoliosis
MC	Major curve Cobb angle
M: F	Male: Female
mL	Milliliter
Mm	Millimeter
MMI	Moss-Miami Instrumentation
OC	Occipitocervical
PS	Pedicle screws
PT	Physical therapy
PSI	Posterior spinal fusion with pedicle screw instrumentation
PJK	Proximal junctional kyphosis
SRS	Scoliosis Research Society
SD	Standard deviation
SPO	Smith-Peterson Osteotomy
TK	Thoracic kyphosis
TLSO	Thoracolumbosacral orthosis
UVI	Uppermost instrumented vertebra
yrs.	Years

List of Original Publications

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

I Ohrt-Nissen S, Lastikka M, Andersen TB, Helenius I, Gehrchen M. Conservative treatment of main thoracic adolescent idiopathic scoliosis: Full-time or nighttime bracing? J Orthop Surg (Hong Kong). 2019 May-Aug;27(2):2309499019860017.

II Oksanen H, Lastikka M, Helenius L, Pajulo O, Helenius I. Posterior Spinal Fusion Extended to Stable Vertebra Provides Similar Outcome in Juvenile Idiopathic Scoliosis Patients Compared with Adolescents with Fusion to the Touched Vertebra. Scand J Surg. 2019 Mar;108(1):83-89.

III Lastikka M, Oksanen H, Helenius L, Pajulo O, Helenius I. Comparison of circular and sagittal reinforced rod options on the sagittal balance restoration in adolescents undergoing pedicle screw instrumentation for idiopathic scoliosis. World Neurosurg. 2019 Apr 14. pii: S1878-8750(19)31020-4.

IV Lastikka M, Aarnio J, Helenius I. Instrumented cervical spinal fusions in children: indications and outcomes. J Child Orthop. 2017 Dec 1;11(6):419-427.

1 Introduction

The paediatric spine can be affected by congenital, developmental, infectious, traumatic and neoplastic disorders, frequently causing a deformity development of the spine (i.e. scoliosis or kyphosis). Several factors make the paediatric spine unique. The growth potential, the need of thoracic height for trunk and lung growth (Lenke et al. 2007), and the small and relatively flexible anatomical structures are all special features of a child's spine.

Idiopathic scoliosis is a three-dimensional deformity of the spine of unknown cause. It can be classified by the age at diagnosis into infantile (0- < 3 years), juvenile (JIS) (3- <10 years) and adolescent (AIS) (≥10 years) forms (James et al. 1954). The infantile form is the rarest with a prevalence of 1% (Konieczny et al. 2013) and AIS is the most common, affecting 2-3% of children (Weinstein et al. 2008). It has been estimated that at least 80% of all idiopathic scoliosis in children are of the adolescent type (Riseborough et al.1973). JIS is defined as a form of idiopathic scoliosis diagnosed between the ages of three and nine years eleven months (James et al. 1954, Lenke et al. 2007). It represents 10-15% of all paediatric idiopathic scoliosis (Coillard et al. 2010). Each form of scoliosis has its own characteristics, which, when taken into consideration, help to guide optimal treatment.

Paediatric spinal deformity may sometimes be liable to require treatment. Untreated JIS is associated with increased mortality (Pehrsson et al. 1992). Untreated AIS is associated with increased back pain (Mayo et al. 1994, Ascani et al. 1986, Helenius et al. 2019). Poor sagittal alignment of the spine is known to decrease the health-related-quality-of-life (HRQoL) in adults (Lafage et al. 2009, Schwab et al. 2013). Several treatment options exist, including physical therapy (PT), bracing, and surgery. Bracing is the golden standard of nonoperative treatment with documented results (Rigo et al. 2003). Bracing results however depend on the amount of brace wear time, i.e. compliance (Weinstein et al. 2013). To improve compliance, a night-time brace has been developed to replace a brace worn full-time. The Providence brace, which is a night-time brace, has yielded good outcomes in the treatment of curves lower in the spine, in lumbar and thoracolumbar regions (D´Amato et al. 2001, Yrjönen et al. 2006), but the current published results with main thoracic curves have been more modest. Thoracic curves in particular are known to be in a higher risk of progression than thoracolumbar and lumbar curves (Ascani et al. 1986, Ohrt-Nissen et al. 2016). We wanted to study which is a more effective brace treatment in main thoracic AIS, a night-time or full-time brace.

Operative treatment aims at a sustainable correction of the deformity in all three dimensions. Posterior spinal fusion with pedicle screw instrumentation (PSI) is currently widely used for spinal deformity correction in AIS (Crawford et al. 2013), but reports in the JIS group are sparser (Sponseller et al. 2016, Sarlak et al. 2009). Because of the great remaining growth potential of the spine in JIS, the development of progressive deformity after PSI, known as distal adding-on or the crankshaft phenomenon, has been noted and published in the literature (Hefti et al. 1983). Several alternatives to avoid this dilemma have been suggested, but it remains unknown whether segmental bilateral pedicle screws (PS) and sufficient length of the fusion would lead to a permanent good outcome.

With operative treatment, to achieve and sustain normal alignment in all three planes is also an issue. Studies have described how sagittal balance in particular is often incomplete, as hypokyphosis (HK) is common in AIS (Flecher et al. 2012, Ohrt-Nissen et al. 2017) and encountered even after PSI. Furthermore, changes in the thoracic kyphosis (TK) have been noted after instrumental spinal fusion (Cheng et al. 2005, Hwang al. 2012a, Lamerain et al. 2014, Kim et al. 2006, Liu et al. 2015). As a solution to achieve good sustained sagittal balance, stronger rods have been used and noted to produce better postoperative TK values (Liu et al. 2015) than rods with lesser stiffness. However, with strong rods the spinal deformity correction procedure of simultaneous coronal correction and TK restoration can become technically more difficult. Increasing rod size can also make the instrumentation bulkier. To make the procedure more applicable, sagittally reinforced rods have been created. These rods are asymmetric, being partially or fully sagittally reinforced, and thus stronger in the sagittal plane but maintaining as narrow a circumference as possible in order not to be overly prominent. Sagittally reinforced rods are consequently stiffer to handle but stronger than traditional circular rods. While publications on reinforced rods exist (Ohrt-Nissen et al. 2017), it is not yet established which is overall the best instrumentation for spinal deformity correction in adolescents with idiopathic scoliosis.

The pediatric cervical spine is a special entity of the spine. It differs from the lower spine both in terms of anatomy and function. Operative treatment has thus certain special features. The bone and ligament structures are small in younger children, and anatomic anomalies are sometimes encountered in syndromes (Ahmed et al. 2008). Associated syndromes are not uncommon in children with cervical spine disorders, and skeletal dysplasia induced cervical instability is currently a common indication for instrumented cervical spinal fusion in children (Helenius et al. 2015). Trauma is another common indication.

Instrumented cervical spinal fusion is overall still seldom needed and thus the procedure is rare and the existing literature on the topic is relatively limited. This makes it difficult for surgeons to gather experience in the treatment of these disorders (Morota 2017). Currently many of the operative techniques, instrumentation, experience and studies include or derive from adults.

Fusion over the craniovertebral junction, i.e. occipitocervical (OC) spinal fusion, has helped the treatment of many pediatric cervical spine pathologies (Vedantam et al. 2017), and the published results have been promising for the treatment of a variety of spinal disorders (Odent et al. 2015). However, as many of these children have much of their growth remaining and/or associated syndromes and comorbities, we sought further to study the indications and outcomes of cervical spinal fusion in children with special interest in the craniovertebral junction and age at surgery. Whether fusion of the craniovertebral junction increases the risk of complications, especially the risk for nonunion, remains unclear. We also sought to report and compare outcomes of cervical spinal fusion in children above and below the age of 10 years.

In this thesis, we sought to study the outcomes of conservative and operative treatment of idiopathic scoliosis and the indications and outcomes of instrumented cervical spinal fusion in children.

2 Review of the Literature

Scoliosis is a three-dimensional deformity of the spine, including coronal, sagittal and rotational deformity (Asher et al. 2006). AIS affects approximately 2-3% of children (Weinstein et al. 2008). AIS affects health and function, as HRQoL and level of function in daily activities have been reported to be lower in AIS patients than in the general population (Freidel et al. 2002, Andersen et al. 2006). While a portion of untreated AIS patients suffer no constraint from the deformity, back pain is a common symptom and has been noted to be more frequent than in children without scoliosis (Danielsson et al. 2001). Back pain together with cosmetic concerns have been described also in adults with idiopathic scoliosis (Weinstein et al. 2003). Back pain is relatively common in AIS, with 25% - 33% reporting back pain at rest and 22% reporting chronic back pain (Makino et al. 2019, Landman et al. 2011). Large postural changes of the spinal alignment, apical vertebrae translation of main thoracic curve, and lumbar hyperlordosis, all of which can be seen in AIS, have been reported to be associated with back pain (Makino et al. 2019).

In AIS, thoracic deformity (i.e. magnitude of the thoracic curve, thoracic hypokyphosis (HK) and coronal imbalance) has been shown to impair pulmonary function (Newton et al. 2005). Thoracolumbar curves, even though not affecting the pulmonary function, are liable to cause cosmetic deformity and back pain (Weinstein et al. 1983 Asher et al. 2006). Untreated JIS is associated with increased mortality due to cardiopulmonary compromise, while untreated AIS is not (Pehrsson et al. 1992). In a long-term FU study, untreated AIS was associated not only with back pain, but also with cardiopulmonary symptoms and psychologic disturbances in patients with greater curve magnitudes (> 40°) (Ascani et al. 1986, Helenius et al. 2019). Several treatment options exist to prevent these symptoms and conditions, and approximately 10% of AIS require some form of treatment (Tambe et al. 2018).

2.1 Treatment: Bracing

Progression of the scoliosis in skeletally immature patients has been reported in 23% of curves between 5°-29° (Lonstein et al. 1984). Thoracolumbar and lumbar curves between 25°-35° have been shown to increase in 66% (Nachemson et al. 1995). Thoracic curves >50° and the lumbar part of a double major curve are known to progress even after skeletal maturity (Weinstein et al. 1983). Curve progression is mainly influenced by the sex of the child, curve pattern (Lonstein et al. 1984) and skeletal maturity (Soucacos et al. 1998, Lonstein et al. 1984). A higher risk for curve progression is associated with thoracic curves (Ascani et al. 1986, Ohrt-Nissen et al. 2016), female gender, right thoracic and double curves in girls, and right lumbar curves in boys, onset of scoliosis before menses, curve magnitudes ≥30°, and pubertal growth spurt (Soucacos et al. 1998).

PT is the first treatment option, and it can also be combined with bracing and operative treatment (Romano et al. 2012). PT has been proven to enhance brace treatment efficiency (Romano et al. 2012) and has been shown to relieve back pain (Zapata et al. 2017). PT however has not been able to correct the existing deformity (Romano et al 2012). Bracing is the golden standard for nonoperative treatment in JIS and AIS. It has been estimated that nearly 10% of AIS progress to a degree that requires brace treatment (Asher et al 2006). Bracing aims at halting deformity progression (Weinstein et al. 2008) while allowing the spine to grow and not to lose its mobility. Bracing has been noted to be effective in preventing curve progression and thus reducing the need for operative treatment (Rigo et al. 2003, Weinstein et al 2013).

In a long-term 20-year FU study on AIS, patients treated with a brace had nearly the same HRQoL as the general population (Danielsson et al. 2001). Despite the satisfactory HRQoL report (Danielsson et al. 2001), more physical complaints, more depression, lower self-esteem and more unhappiness with life have also been described in AIS patients treated with bracing and PT (Freidel et al. 2002). In line with Freidel et al.´s findings, lower HRQoL has also been described in patients treated with bracing compared with the general population (Andersen et al. 2006). The optimal brace treatment protocol is still being developed. Commonly used brace alternatives include a cervicothoracolumbosacral brace (the Milwaukee brace) and thoracolumbosacral orthosis (the Boston brace or TLSO) (Fig.1), the Charleston and Providence brace (Fig.2). The Boston brace or TLSO is a full-time brace, worn 23 h/day, while The Charleston (Price et al. 1997) and the Providence brace (Ohrt-Nissen et al. 2016) are night-time braces, worn while sleeping. Bracing success is multifactorial and is proven to be influenced by compliance (Weinstein et al. 2013), in-brace correction (Chalmers et al. 2015, Emans et al. 1986, Ohrt-Nissen et al. 2016), curve type (Ohrt-Nissen et al. 2016, D´Amato et al. 2001, Thompson et al. 2017), age, curve flexibility and menarchal status (Ohrt-Nissen et al. 2016). Poor compliance has been shown to yield poor outcomes (Weinstein et al. 2013), and to improve patient compliance, a night-time brace has been developed.

In the literature, the Providence brace has given excellent initial in-brace correction and treatment results when treating lumbar and thoracolumbar curves (D´Amato et al. 2001). But these curves are known to be in lower risk of progression than the main thoracic curves. Treatment success in D`Amato et al.´s series was 94%

with lumbar curves and 93% with thoracolumbar but only 43% with thoracic curves. Their study of 102 girls included, however, mainly smaller curves, and only eight had >35° curves. Yrjönen et al. (2006) compared the Providence brace to the Boston full-time brace in 36 AIS girls for thoracolumbar and lumbar curves, and found similarly the Providence brace more effective in preventing curve progression and in providing better in-brace correction for the primary curve. Due to the good results with small thoracolumbar and lumbar curves, the Providence night-time brace has thus been recommended to be used with thoracolumbar and lumbar smaller curves (<35°) (D´Amato et al 2001, Yrjönen et al. 2006). However, the effectiveness of the Providence brace in main thoracic AIS with all curve sizes has not been fully established.

Figure 1. **The Boston brace.** Anteroposterior and side view of the Boston full-time brace (Study I).

Figure 2. **The Providence brace.** Anteroposterior and side view of the Providence night-time brace (Study I).

2.2 Treatment: Operative

When conservative treatment fails or is deemed inadequate, operative treatment may be considered (Fig.3). It has been reported that 0.1% of AIS patients require surgical treatment (Asher et al. 2006). The purpose of surgical treatment is to correct the deformity, improve cosmetic appearance, and prevent future progression with a low complication rate (Tambe et al. 2018). Surgical treatment has been proven to correct the spinal deformity, reduce back pain (Landman et al. 2011) and improve self-image (Rushton et al. 2013), self-esteem and life satisfaction (Zhang et al. 2011). Even though nearly half of the surgically treated AIS patients encounter some limitations to social activities due to their back, the reported HRQoL has been only slightly less than that of the general population (Danielsson et al. 2001, Andersen et al. 2006). Surgically treated AIS patients have been reported to have less pain, better self-image, activity and total SRS-scores then untreated AIS patients (Helenius et al. 2019) and to function at a better daily activities level and have a slightly better HRQoL than patients treated with a brace (Andersen et al. 2006).

A major curve Cobb (MC) angle of ≥45° is often considered as an indication for surgery (Mattila et al. 2013).

The remaining growth of the patient needs to be considered when planning operative treatment. Early spinal fusion in JIS may result in a short trunk and limited lung growth (Lenke et al. 2007). A short thoracic spine correlates with a low forced vital capacity of the lungs and increases the risk of restrictive lung disease (Karol et al. 2008). With significant growth remaining, as is the case in JIS, PSI may result in fusion of the posterior elements of the spine, but the unfused anterior part may continue to grow, creating a progressive deformity (Dubousset et al. 1989, Sponseller et al. 2009). This phenomenon is known as distal adding-on or crankshaft phenomenon (Hefti et al. 1983, Dubousset et al. 1989). To avoid distal adding-on, several alternatives have been recommended; growing rods systems (Lenke et al. 2007), a combined anteroposterior approach (Lenke et al. 2007, Dubousset et al. 1989, Sponseller et al. 2009, Sponseller et al. 2016) and the use of segmental bilateral PS in an posterior only approach (Lenke et al. 2007). In older JIS patients between the age of 9 and 11 years, definitive spinal fusion has been reported to give better deformity correction and to diminish the number of operations needed compared with growing rods (Pawelek et al. 2016). A single posterior approach with definitive spinal fusion is an attractive alternative, as this would simplify the procedure and reduce the need for reoperations and/or an additional anterior approach. In younger JIS patients (with open triradiate cartilage) with more growth potential remaining, a combined anteroposterior approach has been recommended to prevent distal adding-on (Dubousset et al. 1989, Sponseller et al. 2009, Sponseller et al. 2016). In Sponseller's study (Sponseller et al. 2016), extending the posterior spinal fusion to at least the stable vertebrae decreased the risk of curve progression, but did not completely prevent it. However, not all patients in this study were treated with segmental bilateral PS. Thus, it remains unknown whether segmental bilateral PS, fused to the stable vertebra in a posterior only approach, would significantly reduce the risk for distal adding-on and deformity progression during follow-up.

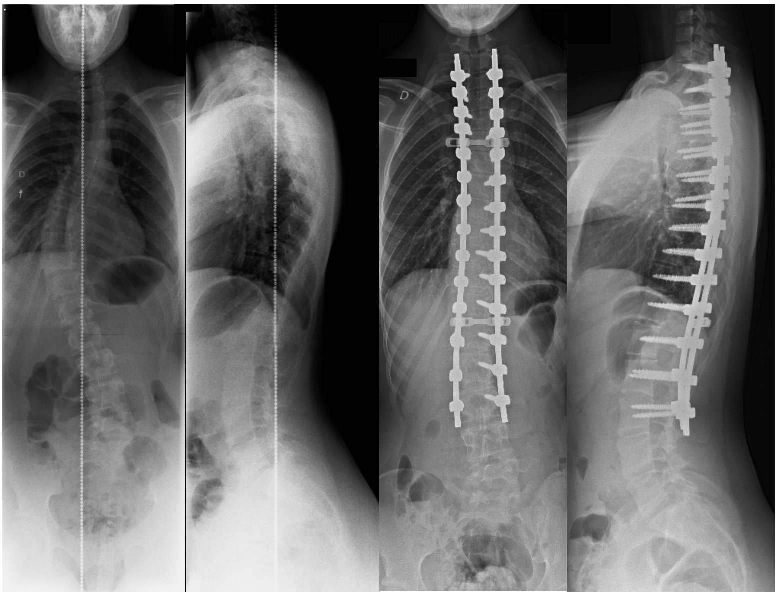

Figure 3. **AIS treated with PSI.** 3-A to 3-D. 14-year-old girl with adolescent idiopathic scoliosis. Preoperative standing radiographs (A, B) demonstrate 47-degree thoracic scoliosis. Standing radiograph (C, D) at two-year FU demonstrate deformity correction with PSI and fusion.

2.3 Sagittal balance

Several studies have emphasized the importance of sagittal balance of the spine in adults (Lafage et al. 2009). Sagittal imbalance has been reported to cause poor health status scores (Glassman et al. 2005), such as the Scoliosis Research Society (SRS) questionnaire and Oswestry Disability Index in adults. Sagittal imbalance correlates linearly with the severity of the back symptoms (Glassman et al 2005). To achieve proper alignment in the sagittal plane as well is a definite goal of spinal surgery in children. This is a concern especially in AIS because hypokyphosis (HK) is common in AIS (Fletcher et al. 2012, Ohrt-Nissen et al. 2017). HK is defined as sagittal profile <10° measured between T5 and T12 vertebrae (Lenke et al. 2001). Moreover, many of the AIS and JIS patients undergoing surgery have been treated previously with a brace, and bracing is known to further flatten the back (Vergari et al. 2019). HK is known to be associated with pulmonary impairment (Johnston et al. 2011, Newton et al. 2005). In the literature, preoperative HK (Lonner et al. 2012, Fletcher et al.

2012, Ohrt-Nissen et al. 2017), smaller diameter rods and male sex (Fletcher et al. 2012) have been noted to be risk factors for postoperative HK after PSI. Additionally, longer spinal fusions and increased number of screws in the construct have been reported to increase the risk for HK (Lonner et al. 2012). In AIS surgery, the fusions are typically long, spanning over 8 or more vertebrae, and are currently usually all screw constructs.

Flattening of the TK occurs already during surgery when the contoured rods with normal TK are placed during the deformity correction manoeuvre (Cidambi et al. 2012). To prevent this, over-contouring of the rods has been recommended. With stainless-steel, approximately 20% flattening of TK intraoperatively has been described (Cidambi et al. 2012). However, the size, shape and material of the rod affect its susceptibility to flatten (Fletcher et al. 2012, Serhan et al. 2013). Changes of the TK have been noted also after surgery. Both decrease (Cheng et al. 2005, Hwang et al. 2012a, Lamerain et al. 2014) and increase (Liu et al. 2015, Kim et al. 2006) of TK have been reported after PSI during FU.

Stronger rods have yielded promising results with better postoperative TK values (Liu et al. 2015, Lonner et al. 2012) than with rods of lesser stiffness. However, thick strong rods can be relatively bulky, and with increased rod stiffness, the procedure can become technically more difficult to perform. Therefore, asymmetrical, partially sagittally reinforced rods have been developed. The hypothesis with asymmetrical, rail like rods is to increase rod strength by sagittal reinforcement while keeping the rod as low profile as possible, hence not being circularly reinforced, which would result in a bulkier rod. (Tambe et al. 2018). In the first study on sagittally reinforced rods, the partially reinforced rail rod was shown to be superior to traditional circular and fully reinforced rods in TK restoration (Ohrt-Nissen et al. 2017). The short-term FU results of sagittally reinforced rods have been promising (Ohrt-Nissen et al. 2017), but the long-term effects of sagittally reinforced rods on the sagittal balance are not yet fully established.

2.4 Cervical spinal fusion

Cervical deformity and instability requiring instrumented spinal fusion is rarely met in children. Typical conditions requiring instrumented cervical spinal fusion in children are cervical spine trauma and various metabolic bone diseases affecting the quality of bone and stability of the OC junction and C1-C2 joint (Dauleac C et al. 2019). Although the number of cervical spinal fusions in adults has increased over the last decade (Salzmann et al. 2018), studies reporting on the indications and outcomes of instrumented spinal fusion in children are still relatively few (De la Garza Ramos et al. 2016, Helenius et al. 2016, Gluf et al. 2005, Hedeqvist et al. 2008, Helenius et al. 2015, Kennedy et al. 2016, Anderson et al. 2006). Because of the rarity of the procedure, many study populations are heterogeneous in nature and relatively few in numbers, including a broad range of aetiologies, comorbidities, age groups including adults, instrumented and non-instrumented fusions, different instrumentations (hooks and wire constructs vs. all screws), and fusions (Ain et al. 2006). Previous publications examining the effects of fusion of the craniovertebral junction (OC) and age are consequently relatively few (Couture et al. 2010, Hwang et al. 2012b, Odent et al. 2015, Vedantam et al. 2017).

Previously, OC spinal fusion has been published to yield promising results, with excellent fusion rate (93%) and few complications (Odent et al. 2015). OC spinal fusion has been successfully done to patients as young as an 18-month-old toddler with skeletal dysplasia without major complications (Oba et al. 2017). OC and non-OC spinal fusion has been reported to yield acceptable patient-reported outcomes, and OC patient-reported scores have been reported to be on the same level as after AIS surgery (Vedantam et al. 2017). However, even with successful surgery and good fusion the OC fusion is not without risks. In a long-term study on OC fusion, adjacent level dislocation was encountered in 20% of the children during the first 3-4 yrs. after surgery (Salunke et al. 2016). Hyperextension of the OC fusion has been associated with adjacent level dislocation in FU (Salunke et al. 2016). As children continue to grow and have much of their life ahead, selecting the most optimal treatment is vital.

Instrumented fusion has been found to be more stable and improve fusion rates compared to non-instrumented alternatives (Hedequist et al. 2016). Screw techniques for the cervical spinal fusion have evolved (Fig. 4) (Harms et al. 2001) and are currently favored over previous semi rigid wiring techniques. They have been proven to further increase fusion rates and decrease the rate of complications (Hwang et al. 2012b, Helenius et al. 2015). Rigid screw instrumentation has currently become the preferred alternative when feasible (Hedequist et al. 2009). Sometimes however the use of screw constructs in small children can be technically challenging, and only semi rigid wiring is possible (Salunke et al. 2016). Wiring is also still applicable as a salvage procedure when screw placement has failed. With both instrumentations, solid fusion over the OC and cervical vertebrae can be achieved. But so far, the long-term outcomes and indications of OC and non-OC fusion are not yet entirely known in children.

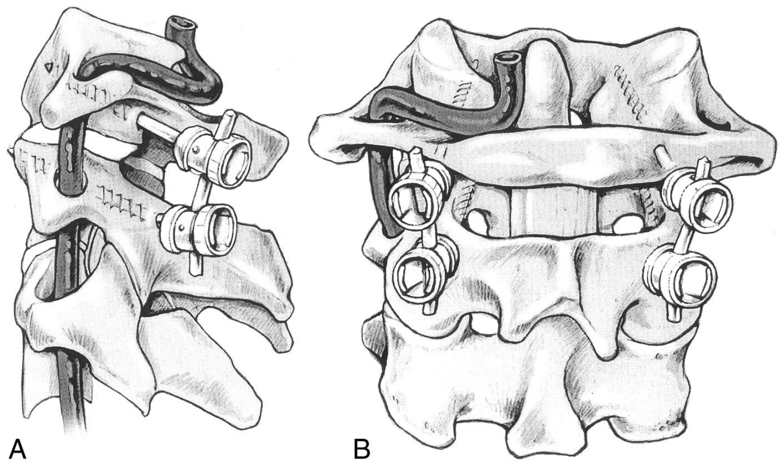

Figure 4. **Cervical spinal fusion screw techniques.** The Harms technique shows C1-C2 fixation with C1 lateral mass screws and C2 pedicle screws (Harms et al. 2001).

3 Aims

1) To compare the effectiveness of the Boston full-time brace and the Providence part-time brace in the treatment of main thoracic AIS.
2) To investigate the outcomes of posterior spinal fusion in JIS and AIS (II).
3) To evaluate if stronger sagittal reinforced rods yield better alignment in adolescents (III).
4) To investigate the indications and outcomes of instrumented cervical spinal fusion in children (IV).

4 Materials and Methods

This thesis is comprised of four retrospective series of paediatric spine patients (Table 1).

Table 1. Clinical Characteristics of the Study Groups (Study I-IV).

	Study I		**Study II**		**Study III**		**Study IV**
	Boston brace	Providence brace	JIS	AIS	Circular rod	Reinforced rod	
n	37	40	21	84	54	36	35
Mean age$^{\beta}$	12.6	12.6	12	15.8	16	16	9.9
Gender (M/F)	1/36	1/39	1/20	23/61	11/43	9/27	21/14
Mean FU, yrs.	2.1	2.1	2.2	2.1	2.1	2.1	2.1

$^{\beta}$ Age at the beginning of treatment.

4.1 Patients

The patients in study I were enrolled between 1/2009 and 12/2015 in Rigshospitalet, Copenhagen, Denmark, and the Turku University hospital in Finland. The inclusion criteria were AIS with main thoracic curves of MC between ≥ 25° and <40°, with apex of the curve between Th7 and Th11 and Risser ≤ 2 requiring brace treatment. The study included 77 patients, 40 in the Providence group and 37 in the Boston group. Mean age was 12.6 years. The treatment was conducted parallel between the two centers. Furthermore, all the brace treated patients who met the inclusion criteria were included consecutively. The groups were similar in the beginning of treatment for age, gender, body mass index and menarchal status.

Patients in study II were enrolled between 2009 and 2015 in the Turku University hospital. The inclusion criteria for JIS patients were diagnosis of JIS, Risser 0, without associated spinal cord anomalies or syndromes. The inclusion criteria for

AIS were diagnosis of AIS Risser ≥2, age between 13-18 years. Operative indication was a major curve Cobb angle of ≥ 45° in all the patients (Mattila et al. 2013). In JIS, an additional prerequisite for operative treatment was estimated thoracic spinal height of ≥ 22 centimeters after correction of the spinal deformity. Twenty-one children filled the inclusion criteria for JIS (of these 15 were with open triradiate cartilage). In addition, 84 AIS patients were enrolled consecutively under the same time period to create a comparison group with a 1:4 ratio. The mean age in the JIS group was 12.0 years and in the AIS group 15.8 years.

Patients in study III were enrolled between 2012 and 2018 in the Turku University hospital. The inclusion criteria were idiopathic scoliosis with an MC of ≥ 45° that required operative treatment in the adolescent age. Ninety consecutive children were included in the study. The mean age at surgery was 15.6 years.

The patients in the study IV were enrolled between 2005 and 2015 in Turku University hospital and Helsinki University hospital. The inclusion criteria were cervical instability or deformity requiring instrumented spinal fusion under the age of 18 years. The indications for surgery were cervical instability due to trauma, an increased atlantoaxial distance ≥ 5 mm; space available for the cord < 13 mm; Basilar invagination, which was defined as odontoid abnormally extending above the basion-opisthon line (McRae 1953) and subaxial kyphosis of ≥60°. Altogether 35 children were included in the study. The mean age at surgery was 9.7 years (Table 4).

4.2 Methods

Study I was conducted in the Rigshospitalet in Copenhagen, Denmark, and the Turku University hospital in Turku, Finland. Study I compared two series of patients with main thoracic AIS treated with a brace during the same time period. In Rigshospitalet, the treatment was a night-time brace with a Providence brace worn during sleep, approximately 8h/day, while in Turku University hospital the treatment was a full-time Boston brace, worn 23h/day. Both braces were custom made to fit the patient and correct the existing deformity (Emans et al. 2003). The Providence braces were based on measurements and the Boston braces were made from prefabricated models, which were customized based on radiographs. All the patients were followed up until the end of brace treatment. Brace treatment ended when skeletal maturity was achieved or when curve progression led to surgery. Skeletal maturity was defined by Risser ≥4 and/or over 2 years past menarche. The study subjects were followed in the out-patient clinic in the beginning on treatment, during treatment and at the end of treatment. The following radiographs were measured: the last radiographs preceding brace treatment, initial standing (Boston) or supine (Providence) in-brace radiographs in the beginning of the treatment, and standing radiographs without the brace at the last FU. The patients spent the night before the radiography without the brace.

Radiographic measurements were done during the (FU) visits, and curve progression was measured by the authors. All the patients had finalized brace treatment during the study, and treatment success was defined as MC ≤45° at the end of treatment. Mean FU was 2.1 years.

Study II was a retrospective comparative cohort study on the clinical, radiographic, and HRQoL using the Scoliosis Research Society 24 outcome questionnaire (SRS-24) (Haher et al. 1999). All the patients were operated on in the Turku University hospital with segmental bilateral PS with en bloc DVR (6.35 CD Legacy or Solera 6.0, Medtronic Spinal and Biologics, Memphis, TN, USA) in a posterior only approach, by the same two experienced spine surgeons. The study subjects were followed in the out-patient clinic before surgery, and at six months and two years postoperatively with standard standing radiographs. Immediate postoperative assessment was done at the ward. Bending radiographs were taken preoperatively. The following measurements were made from the radiographs: the proximal thoracic, main thoracic, and thoracolumbar / lumbar curves, coronal and sagittal balance, TK (T5-T12), lumbar lordosis (T12-S1) measured by the Cobb technique. In JIS, the spinal fusion was extended to the stable vertebra (i.e. the most proximal vertebra where the central sacral vertical line (CSVL) falls between the pedicles). In AIS patients, the fusion was extended only to the touched vertebra (i.e. the lowest vertebra touched by the CSVL). Mean FU was 2.1 years.

Study III was a retrospective comparative cohort study on the clinical, radiographic, and HRQoL using the SRS-24 questionnaire (Haher et al. 1999). All the patients were operated in the Turku University hospital with segmental bilateral PSI with en bloc DVR, using a posterior only approach by the same two experienced spine surgeons or under their direct supervision in the operation theater. All the patients were operated on with 6.0 mm CoCr rods (Solera 5.5/6.0 Instrumentation, Medtronic). The first group were operated on with circular rods, and the second group were operated on with sagittal reinforced rods. The circular rod group included 54 patients (43 females), and the reinforced rod group included 36 patients (27 females). The reinforced rod group included partial reinforced rods (19 patients) and full reinforced rods (17 patients). Both rods were sagittal reinforced, and thus stronger in the sagittal plane than the circular alternatives. The partial reinforced rod is circular in the proximal and distal end of the rod and reinforced in the middle part, while the full reinforced rod is sagittal reinforced along the entire length of the rod. Rod selection was done consecutively, so that the first 54 children were operated on using circular rods, the following 19 with partial reinforced rods and the final 17 with full reinforced rods. The study subjects were followed preoperatively, immediately postoperatively, at six months and at two years postoperatively with standard standing radiographs. Bending radiographs were taken preoperatively. Following measurements were made from the images: the proximal thoracic, main thoracic, and thoracolumbar / lumbar curves, coronal and sagittal balance, TK (T5-T12 and T1-T12), proximal junctional kyphosis (PJK) and lumbar lordosis (T12-S1) measured by the Cobb technique. PJK was measured at the two adjacent vertebrae above the uppermost instrumented vertebra (normal range <20°). Thoracic kyphosis of < 10° measured between T5-T12 was classified as hypokyphosis. Operative technique and screw placement were standardized. Fifty-three (98%) patients in the circular rod group and twenty-four (67%) in the reinforced rod group had 2-year FU available, the rest had a minimum of 6 months FU.

Data on the indications and outcomes of cervical spinal fusion performed by a single experienced spine surgeon at the Turku University hospital and the Helsinki University hospital were retrospectively collected from a pediatric spine register (Study IV). We gathered the following data: clinical presentation leading to diagnosis; presence or absence of symptoms (i.e. neck pain, torticollis or head tilt); neurologic function pre-operatively, postoperatively and at final FU, according to the motor function scoring system of the Japanese Orthopedic Association (JOA) (Miyoshi et al. 2004). Twenty patients (57%) had a JOA score available.

All patients had pre-operative lateral cervical spine radiographs or advanced imaging with CT or MRI. The images were analysed for the presence or absence of cervical kyphosis, odontoideum or dysmorphic dens, whether spinal fusion was achieved or not, and instrumentation status (i.e. implant failure). The images were further analysed for the space available for the cord at the narrowest segment. The presence of a high signal area in the spinal cord, a spinal cord syrinx; a high-riding vertebral artery, vertebral dysplasia and dural ectasia were recorded. Mean FU was 2.1 years (1.0 to 5.0) in surviving patients.

4.2.1 Statistical analysis

The data that did not follow normal distribution is given as percentages (%) or median, and the data that followed normal distribution is given as mean ± standard deviation (SD).

The distribution of all continuous variables that did not follow normal distribution (study II) were tested using the Mann-Whitney U test for between group and Wilcoxon signed rank sum test for within group comparisons (Study I, II). The statistical significances of the unadjusted differences between frequency distributions were tested with Pearson's chi square test (Study I, II, and IV).

The distribution of all continuous variables that did follow normal distribution were tested using the One-Way Anova and Kruskal-Wallis test (study III) and paired or unpaired t test (study IV). Association between groups and hypokyphosis (categorized below < 10° and ≥ 10°) was tested with chi square test (study III). Correlation between correction percentage and TK was calculated with Pearson correlation coefficient (study III). JMP® Pro 13 (Brady, USA) (Study III) and Excel (Microsoft, USA) were used for statistical calculations (study II, III). P values of 0.05 or below were considered statistically significant.

4.2.2 Ethical Aspects

The Ethics Committee of our university hospital granted approval for the study. No additional patient contact was needed for these studies, and therefore a written informed consent was not requested by the Ethics committee.

5 Results

5.1 Conservative brace treatment outcomes in main thoracic AIS

Seventy-seven patients were enrolled in this study, 40 in the Providence group and 37 in the Boston group. The treatment period was 2.1 years (median) in both the Providence and the Boston groups ($p \geq 0.11$). The Providence group had a larger initial main curve than the Boston group, median MC 36° and 29° in the Providence and the Boston groups, respectively ($p<0.01$) (Table 2).

Curve progression to ≥45° was noted in 16 (43%) and 13 patients (35%) in the Providence and Boston groups, respectively ($p=0.84$). Curve progression of >5° was noted on 22 (55%) and 23 patients (62%) in the Providence and the Boston groups, respectively ($p=0.69$) (Fig.1). During the study period, MC progression was a median of 7° in the Providence group and 8° in the Boston group ($p = 0.74$) (Fig. 5). The Providence brace and the Boston brace were equally effective in the treatment of main thoracic AIS. The initial curve size at the beginning of treatment had most impact on treatment outcomes ($p=0.02$). Age at the beginning of treatment was not associated with an increased risk of curve progression ($p=0.39$).

Table 2. Radiographic Outcomes (Study I).

	Providence brace	Boston brace	p-value
Beginning of treatment			
Major curve (°)	36	29	<0.01
In brace correction (%) $^{\beta}$	68	30	<0.01
TL/L curve (°)	23	19	0.014
PT curve (°)	21	15	<0.01
Last FU			
Major curve (°)	44	39	0.06
TL/L curve (°)	28	23	<0.01
PT curve (°)	25	17	<0.01

Values indicate mean unless otherwise specified; TL/L, Thoracolumbar curve; PT, proximal thoracic curve; FU, follow-up; MC, Major curve Cobb angle; α, Major coronal curve progression; $^{\beta}$ The correction percentage of the initial curve done by the brace.

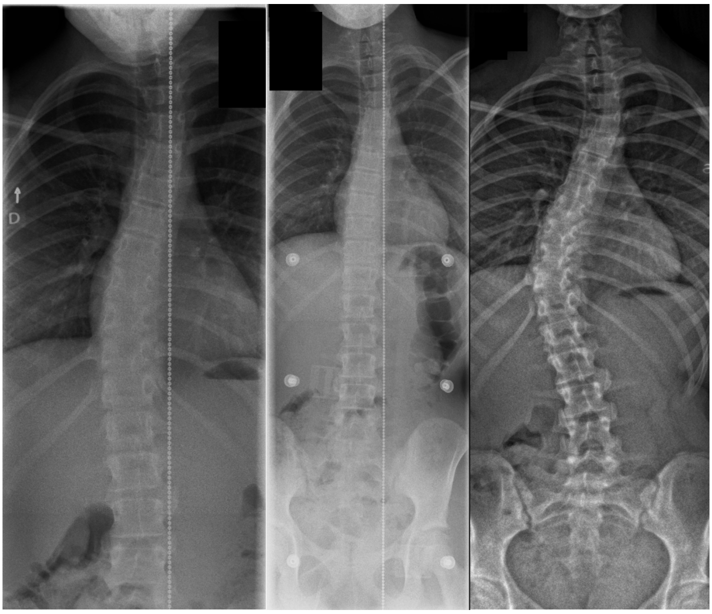

Figure 5. **Boston brace treatment:** Figs. 1-A to 1-C. 11-year-old girl with adolescent idiopathic scoliosis. Pretreatment standing radiographs (A) demonstrate a 25-degree thoracic scoliosis. Standing radiographs in brace (B) show an improved thoracic curve to 7 degrees and at 3.5-year FU (C) demonstrate a 38-degree main thoracic curve without requiring surgery.

5.2 Comparison of surgical outcomes for juvenile vs. adolescent idiopathic scoliosis (Study II)

The JIS group also had a larger number of girls than boys when compared to the AIS group (p=0.03). JIS patients had more spinal levels fused (p=0.01) and more posterior column osteotomies (p=0.01) than the AIS group. JIS patients had larger preoperative MC than AIS patients (58° vs. 53°, p<0.01). MC averaged 13° and 12° in the JIS and AIS groups at two-year FU with correction percentages of 78% and 77% in the JIS and AIS groups, respectively (p=0.90) (Table 4).

In the sagittal plane, TK measured 21° in the JIS and AIS groups preoperatively (p=0.84), and 17° and 19° in the JIS and AIS groups, respectively, at two-year FU (p=0.54) (Fig.6). HK was found in 4 patients (19%) preoperatively in JIS and in one patient (1.2%) in AIS groups (p<0.001). HK at two-year FU was noted in three patients (14%) in the JIS and seven (8.3%) in the AIS groups (p=0.48). Proximal junctional kyphosis (PJK) was not noted in the JIS group, and only two patients (2.3%) with AIS had PJK at 2-year FU (p=0.48).

There was no difference in the number of complications between the groups. There were two complications (9.5%) in the JIS group and four (4.8%) in the AIS group (p=0.80). In the JIS group, the complications included one intraoperative dural lesion and one deep wound infection, while in the AIS group all the complications were related to pedicle screws.

The JIS group had better SRS-24 scores than the AIS control group for total score ($p=0.04$), back pain ($p=0.04$), function from back condition ($p=0.04$), and satisfaction ($p<0.05$) at two-year FU (Table 5). Both JIS and AIS groups had an improvement in the back-pain score from preoperative to two-year FU ($p<0.01$ for JIS and for AIS).

Distal adding-on (>10°) was noted in only 4 patients in the entire cohort. In the JIS group one patient (4.8%) and in the AIS group three patients (3.6%) had distal adding-on ($p=0.80$). The distal adding-on was noted so modest that none required operative treatment.

Table 3. Clinical Characteristics of the Study Groups (Study II).

	Juvenile (n=21)	**Adolescent (n=84)**	**p-value**
Age at surgery, years	12.0 ± 1.3	15.8 ± 1.5	<0.001
Gender (M/F)	1/20	23/61	0.027
Mean follow-up, years	2.2 ± 0.3	2.1 ±0.3	0.81
Open triradiate cartilage (n)	15	0	<0.001
Lenke classification (n)*			
1	3	30	N.S.
2	5	28	
3	8	6	
4	3	4	
6	2	16	
Number of levels fused (n)	10.9 ± 1.4	10.0 ± 1.4	0.012
Posterior column osteotomies, (n, %)	12 (57.1%)	24 (28.6%)	0.014
Operative time, hours	3.7 ± 0.9	3.4 ± 1.1	0.11
Intraoperative blood loss(mL)	737 ± 405	561 ± 316	0.076

Values indicate mean ± SD unless otherwise specified; *Lenke classification for juvenile idiopathic scoliosis (Lenke et al. 2007) and for adolescent idiopathic scoliosis (Lenke et al. 2001). Table III modified from original publication II.

Table 4. Radiographic Outcomes (Study II)

	Juvenile (n=21)	Adolescent (n=84)	p-value
Major curve (°)			
Preoperative	58.0 ± 8.1	53.0 ± 7.1	0.0032
On bending	40.9 ± 15.8	34.9 ± 11.9	0.20
At six months	14.0 ± 4.8	12.1 ± 5.9	0.16
Correction (%)	75.4 ± 9.8	77.3 ± 11.2	0.58
At two-year	12.7 ± 4.5	12.3 ± 6.3	0.45
Correction (%)	78.2 ± 7.7	76.9 ± 10.8	0.90
Th kyphosis (T5-T12, °)			
Preoperative	20.9 ± 14.6	21.0 ± 14.2	0.84
At six months	18.5 ± 13.0	18.8 ± 8.7	0.91
At two-year	16.6 ± 8.1	19.4 ± 8.8	0.54
Lordosis (T12-S1, °)			
Preoperative	53.5 ± 10.6	51.1 ± 12.1	0.67
At six months	48.5 ± 11.4	47.8 ± 10.4	0.88
At two-year	46.3 ± 18.1	47.3 ± 12.1	0.95
Coronal balance (mm)			
Preoperative	7.6 ± 14.6	2.7 ± 17.5	0.016
At two-year	2.7 ± 13.4	1.5 ± 10.9	0.15
Sagittal balance (mm)			
Preoperative	14.6 ± 23.2	13.4 ± 22.0	0.78
At two-year	4.6 ± 27.4	5.5 ± 19.9	0.17

Values indicate mean ± SD. Table 4 modified from original publication II.

Table 5. Outcomes of the Scoliosis Research Society (SRS) 24 Questionnaire (Study II).

SRS Score	Juvenile (n=21)	Adolescent (n=84)	P value
Pain			
Preoperative	3.5 ± 0.5	3.5 ± 0.5	0.84
At six months	4.5 ± 0.4*	4.3 ± 0.6*	0.11
At two-year	4.6 ± 0.4**	4.3 ± 0.5*	0.040
General self-image			
Preoperative	3.8 ± 0.7	3.7 ± 0.6	0.82
At six months	4.2 ± 0.6	4.0 ± 0.7	0.64
At two-year	4.4 ± 0.7	3.9 ± 1.0	0.063
Function from back condition			
Preoperative	4.2 ± 0.2	3.9 ± 0.5	0.084
At six months	4.0 ± 0.5	4.0 ± 0.5	0.96
At two-year	4.4 ± 0.7	4.0 ± 0.9	0.040
Postoperative self-image			
At six months	3.3 ± 0.6	3.2 ± 0.5	0.64
At two-year	3.5 ± 0.6	3.1 ± 0.8	0.075
Postoperative function			
At six months	2.2 ± 0.9	2.0 ± 0.9	0.47
At two-year	3.1 ± 0.3	2.5 ± 1.0	0.072
Satisfaction			
At six months	4.4 ± 0.5	4.1 ± 0.8	0.25
At two-year	4.5 ± 0.5	3.9 ± 1.1	0.049
Total SRS-24 score			
At six months	95.6 ± 9.6	92.5 ± 9.8	0.26
At two-year	101.4 ± 6.1	96.7 ± 9.3	0.040

Values indicate mean ± SD; *Preoperative vs. follow-up p≤0.001; **p=0.0039. Table 5 modified from original publication II.

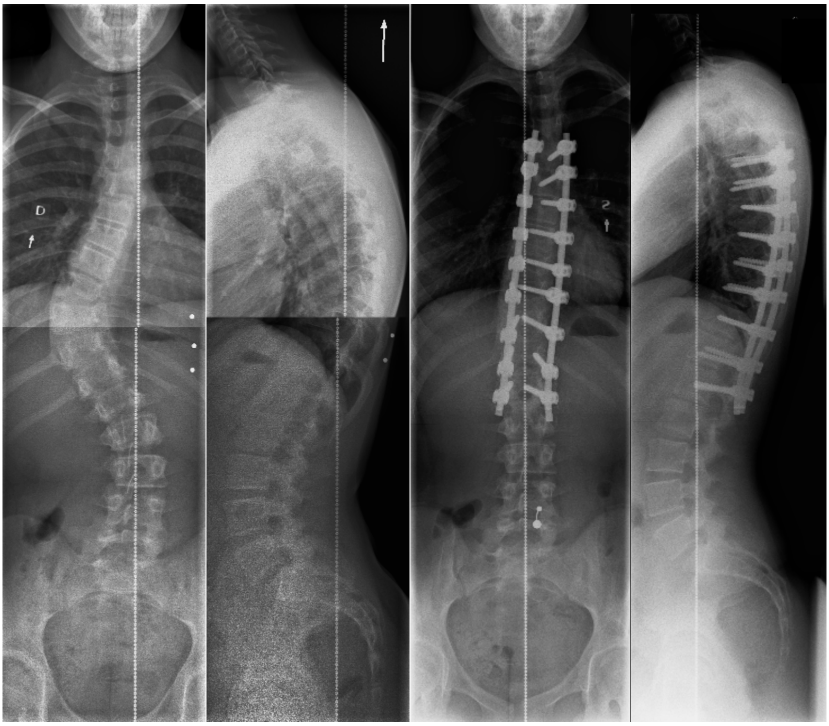

Figure 6. **JIS:** Figs. 2-A to 2-C. 11-year-old girl with juvenile idiopathic scoliosis (Risser 0). Preoperative standing radiographs (A, B) demonstrate 60-degree thoracic scoliosis. Standing radiographs (C, D) at two-year FU demonstrate fusion after PSI with no adding-on and normal TK.

5.3 Comparison of circular and sagittal reinforced rod options on the sagittal balance restoration in adolescents undergoing pedicle screw instrumentation for idiopathic scoliosis (study III)

The groups were similar in preoperative clinical characteristics, in HRQoL, and in preoperative radiographic measurements. The circular rod group had fewer posterior column osteotomies done than the reinforced rod group (p=0.04) (Table 6.

In the coronal plane, major curves were mean 52° and 55° preoperatively, 10° and 14° at six months and 11° and 14° at two-year FU, with correction percentages of 78% and 69% in the circular and reinforced rod groups, respectively (p<0.01) (Fig. 7, Table 7).

In the sagittal plane, the mean TK was preoperatively 19° in both groups and 16° and 20° at six months FU, and 16° and 21° at two-year FU in the circular and reinforced rod groups (p<0.01) (Fig. 8).

Preoperatively, HK was found in 12 (22%) and 5 (14%) patients in the circular and reinforced rod groups (p=0.32) and in 8 (14%) patients in the circular rod group but in none in the reinforced rod group at two-year FU (p= 0.02). PJK was not noted in neither group during the study period, and there were no differences between the groups in the HRQoL during the FU.

There was a negative correlation between coronal curve correction and TK in the reinforced rod group (r = -0.52, p<0.01), but not in the circular rod group (r= 0.03, p=0.8).

Table 6. Clinical Characteristics of the Study Groups (Study III).

	Circular rod (n=54)	**Reinforced rod (n=36)**	**p-value**
Age at surgery (yrs)	16 ± 2.1	16 ± 2.1	0.71
Gender (M:F)	11 : 43	9 : 27	0.60
Mean follow-up, (yrs)	2.1 ± 0.2	2.1 ± 0.3	0.13
Lenke type (n)†			
1	18	15	N.S
2	20	13	
3	1	2	
4	3	5	
5 or 6	12	1	
Operative time, hours	2.7 ± 0.7	2.7 ± 0.6	0.68
Intraoperative blood loss (mL)	500 ± 290	470 ± 360	0.72
Number of levels fused (n)	10 ± 1.4	11 ± 1.8	0.32
Posterior column osteotomies (n)	2.4 ± 0.8	3.3 ± 1.2	0.04
Total SRS-24 score‡			
Preoperatively	4.1 ± 6.3	3.9 ± 9.5	0.14
At six months	3.8 ± 11	3.8 ± 11	0.82
At two-year	4.1 ± 10	4.1 ± 12	0.99

*Values indicate mean ± SD unless otherwise specified; †Lenke classification for juvenile idiopathic scoliosis and for adolescent idiopathic scoliosis (Lenke et al. 2001); ‡ SRS-24 = Scoliosis Research Society 24 outcome questionnaire (Haher et al. 1999); average amount of points per question; mL, milliliter. Table 6 modified from original publication III.

Table 7. Radiographic Outcomes (Study III).

	Circular rod (n=54)	**Reinforced rod (n=36)**	**p-value**
Major curve (°)			
Preoperative	52 ± 5.7	55 ± 10	0.08
On bending radiograph	36 ± 13	38 ± 13	0.42
Correction (%)[β]	31	31	1
At six months	10 ± 5	14 ± 6.7	0.01
At two year	11 ± 4.9	17 ± 7.2	<0.01
Correction at two year (%)	78 ± 10	69 ± 12	<0.01
Th kyphosis (T5-T12 °)			
Preoperatively			
At six months	19 ± 12	19 ± 11	0.87
At two year	16 ± 6.7	20 ± 7.5	0.04
	16 ± 7	21 ± 6	<0.01
Lordosis (T12-S1, °)			
Preoperatively	50 ± 12	51 ± 11	0.56
At six months	50 ± 11	46 ± 12	0.2
At two year	49 ± 12	52 ± 12	0.38
Sagittal balance (mm)			
Preoperatively	7.8 ± 23	14 ± 27	0.24
At six months	3.6 ± 19	9.4 ± 28	0.26
At two year	0.0 ± 29	0.0 ± 22	0.99
PJK *(°)†*			
At six months	9.4 ± 6.8	8.8 ± 4.3	0.63
At two-year	8.7 ± 6.5	7.6 ± 6.6	0.5

*Values indicate mean ± SD in parenthesis unless otherwise specified; † PJK measured at two adjacent vertebrae above UIV (Yagi et al. 2011); [β] Correction percentage of major coronal curve measured from immediate postoperative radiographs. Table 7 modified from original publication III.

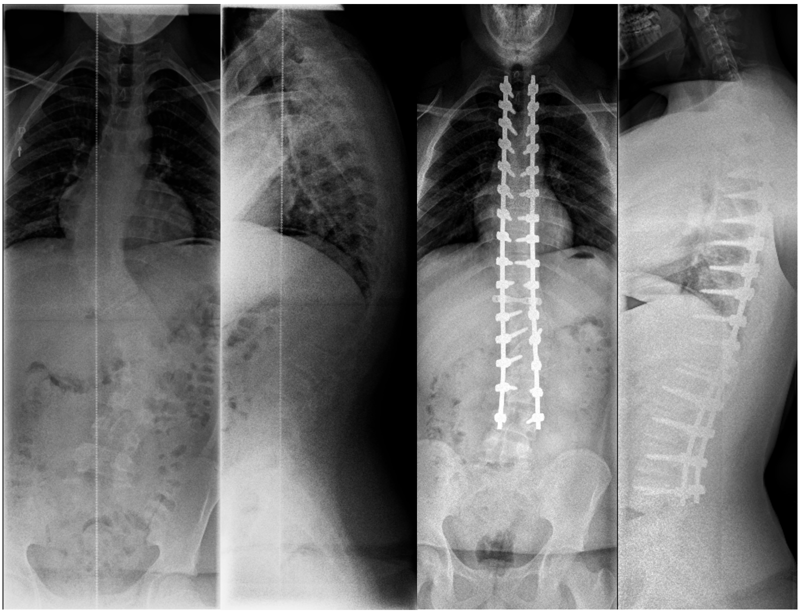

Figure 7. Circular rod instrumentation: Figs. 3-A to 3-D. 14-year-old boy with adolescent idiopathic scoliosis. Preoperative standing radiographs (A, B) demonstrate 59-degree thoracolumbar scoliosis. Standing radiographs at two-year FU (C, D) demonstrate circular rod instrumentation.

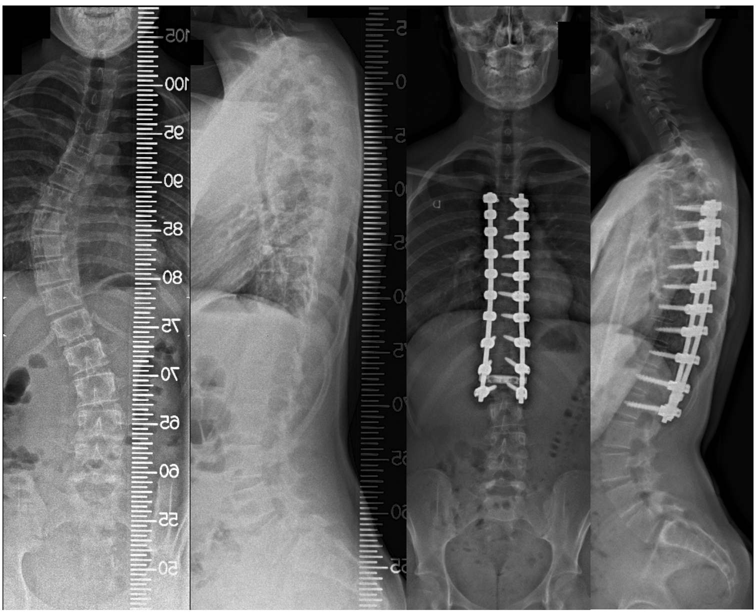

Figure 8. Reinforced rod instrumentation: Figs. 4-A to 4-D. 15-year-old boy with adolescent idiopathic scoliosis. Preoperative standing radiographs (A, B) demonstrate 45-degree thoracic scoliosis with hypokyphosis. Standing radiographs at two-year FU (C, D) demonstrate sagittal reinforced rod instrumentation with normal thoracic kyphosis.

5.4 Occipitocervical and cervical spinal fusion: indications and outcomes

The main indications for instrumented cervical spinal fusions in children in the current series were skeletal dysplasia associated cervical instability and cervical spine injuries (Table 8).

23 (67%) children were operated on for skeletal dysplasia (Fig. 9) and 12 children were operated on for trauma (Fig. 10). Twenty-one of the 23 skeletal dysplasia patients underwent primary spinal fusions and two were revisions. All the trauma patients underwent primary spinal fusions.

Complications were observed in 12 (34%) patients, with multiple complications in four (11%). Four (11%) children needed one or more revisions, three for non-union and one for graft dislodgement. Complications were encountered in 39% of those operated for skeletal dysplasia and in 25% of those operated for trauma, but the difference was not statistically significant ($p = 0.177$) No significant difference was found in the incidence of complications between surgical approaches (anterior vs posterior vs combined antero-posterior approach) ($p = 0.372$). In the current series, there was only one nerve injury due to surgery. The patient had a C7 aneurysmal bone cyst with a pathological fracture and required C7 excision and fusion. The C8 nerve root injury was identified intraoperatively and persisted during the FU period.

All the patients of this series survived the instrumented cervical spinal fusion operation and 94% survived through the FU. One two-year-old child died in the immediate postoperative period because of the severity of the trauma that led to surgery. The patient suffered a traumatic C6-C7 spinal cord transection and L2-L3 chance fracture from a vehicle accident. One nine-year-old child with a VATER association died 2.5 years after an OC fusion because of difficulties in tracheal intubation during induction of anesthesia (Table 9).

Table 8. Preoperative Demographics (Study IV).

Pt. No.	Age at surgery (yrs.)	Indication for surgery	Basic diagnosis	Space available for the cord (mm)
1	13.1	C1-2 instability	Psoriasis artropathy	17
2	17.2	C1-2 instability, medulla compression	Metatrophic dysplasia	19
3	8.4	AARF	Down syndrome	20
4	12.1	AARF		15
5	5.8	C1-2 instability, C1-2 spinal stenosis	Morquio type B, os odontoideum	20
6	6.6	C1-2 instability	Metaphyseal chondrodysplasia	15
7	5.5	C1-2 instability, C1-2 spinal stenosis	C1 assimilation, C2/C3 block vertebra	15
8	13.5	C5-6 instability	Polyarticular Juvenile Arthritis	10
9	11.5	AARF		16
10	11.5	Os odontoideum	Gorlin syndrome	12
11	9.5	Kyfoscol.sec.cervicothor. with C 6-7 luxation	Neurofibromatosis	8
12	10.6	C1-2 instability	OI	14
13	6.0	C1-2 instability	C1 assimilation, C2/C3 block vertebra	11
14	14.0	Bilateral occipital condyle fracture with C0-1 instability	Trauma	19
15	14.7	C5 burst fracture with tetraparesis	Trauma	9
16	2.6	C6-7 Fracture luxation, transection medullae, L2-3 Change Fr,	Trauma	6
17	15.5	C6 Fr, C5-6 unilateral luxation	Trauma	13
18	14.7	C5-6 fracture luxation	Trauma	12
19	14.5	C2-3 post-traumatic instability	Trauma	14
20	15.1	C7 pathological fracture	C7 ABC	14
21	11.0	Infantile fibrosarcoma, C6 local tumor recurrence	Primary esophageal tumor	14
22	4.5	C1-2 instability, C1 occipitalization	VATER	12
23	9.0	C1 hemiatlas, hypoplastic dens, congenital spinal stenosis	Goldenhar syndrome	9
24	8.5	C1-2 instability,	Myelomeningocele	12
25	14	AARF	Failed conservative treatment	14
26	11.0	C6-7 fracture dislocation	Trauma	8
27	8.0	Basilar invagination with hydrocephalus	OI type III	9
28	5.0	Subaxial instability with medullopathy due to failure of fixation after C5 corpectomy	Chrondrodysplasia punctata	3
29	6.0	C1 hemiatlas	Klippel-feil syndrome	14
30	12.1	Cervical spine kyphosis after post laminectomy	Neurofibromatosis type 1	10
31	5.4	C1-2 instability, hypoplastic dens	SED	14
32	7.7	C1-2 instability, hypoplastic dens	SED	15
33	5.0	C1-2 instability, C0-2 stenosis	SED	15
34	4.0	C2 Dens fracture	Trauma, conservative treatment failed	10
35	6.5	C2-3 instability and stenosis	Klippel feil syndrome	8

NA, not available; VATER: Vertebral, Anal, Tracheo-Esophageal, Radial/Renal association; AARF, atlantoaxial rotatory fixation; OI, osteogenesis imperfecta; SED, spondyloepiphyseal dysplasia; Fr, Fracture. Table 8 modified from original publication IV.

Table 9. Surgical Data at Final Follow-up (Study IV).

Pt. No.	Age (yrs.)	Fusion location; surgical procedures	Complication
1	15.0	C1-2; ICBG	None
2	21.8	C0-2; occiput plates, hooks decompression, ICBG, BMP	None
3	9.9	C1-2;ICBG, BMP	Transient MEP loss during reduction
4	14.3	C1-2;ICBG	None
5	8.2	C0-3; occiput plate, hooks, decompression, ICBG	Anchor site breakage, longer fusion then planned
6	8.6	C1-2; C1 LMS, C2 PS, ICBG	None
7	9.0	C1-2; ICBG, bone paste	None
8	15.6	C5-6; anterior plate, discectomy, ICBG, bone paste	None
9	13.8	C1-2; ICBG	None
10	13.7	C1-2;decompression, ICBG	None
11	11.1	C1-Th9; decompression, ICBG, DBX	None
12	12.1	C1-2; ICBG	None
13	7.4	C0-2;decompression, ICBG	None
14	16.0	C0-2; ICBG	None
15	18.2	C4-6; anterior plate, C5 corpectomy, decompression, ICBG; Posterior LMS	None
16	*	C2-Th3, L2-3; decompression ICBG, DBX	Deceased due to associated injuries.
17	16.5	C5-7; C6 nerve root decompression l.dx, ICBG	None
18	15.7	C5-6; anterior plate, discectomy, cage, C5 laminectomy, decompression, ICBG, DBX	None
19	15.0	C2-3; ICBG, DBX	None
20	19.1	C6-Th1; ICBG tumor C7 block excision	C8 nerve root injury
21	14.0	C5-Th3; anterior plate, decompression, ICBG	Subclavian artery lesion. Revised for graft dislodgement and deep wound infection.
22	6.5	C0-4; occiput plate and hooks, decompression, ICBG	Died for difficult airway 2.5 years postoperatively
23	13.0	C0-5; occiput plate and hooks, decompression, ICGB	Rigid rod broke during follow up. Dural tapping
24	10.5	C1-2; transarticular screws, C1 laminar hooks, ICBG	None
25	16.0	C1-2; transarticular screws, C1 laminar hooks, ICBG	None
26	13.0	C5-Th1; C5-7 LMS, Th1 hooks, ICBG	None
27	13.0	C0-Th2; occiput plate, hooks, C1 laminectomy, foramen magnum decompression, autograft	Hypoglossus paresis. Rods broken 2.5 yrs. after primary surgery. Revised for nonunion.
28	9.0	C0-Th5; occiput plate, hooks, C3-5 laminectomy, decompression, ICBG, allograft	Early failure of fixation. Rods broken 1.5 yrs. after first revision. Second revision with combined approach for nonunion.
29	9.0	C0-5; C1 laminectomy, decompression, occiput plate, hooks, ICBG	None
30	16.4	C2-Th2; C2-C7 LMS; Th1-2 PS, ICBG	Dural ectasia continues with further vertebral body scalloping
31	9.4	C1-2; wiring, ICBG	Vertebral artery tapping
32	11.7	C1-2; transarticular screws, wiring, ICBG	None
33	10.0	C0-2; occiput plate, wiring, decompression, ICBG	Revised for nonunion.
34	6.0	C1-2; C1 LMS, C2 PS, decompression, ICBG	None
35	8.0	C1-4; C1, C4 LMS, decompression ICBG	None

NA, not available; ICBG, iliac crest bone graft; PS, pedicle screw; BMP, bone morphogenic protein 2; DBX, demineralized bone matrix; LMS, lateral mass screws; allograft, allograft bone graft; bone paste, synthetic osteoconductive bone paste, a bone graft substitute; *no follow-up because of death shortly after index surgery due to associated injuries. Table 9 modified from original publication IV.

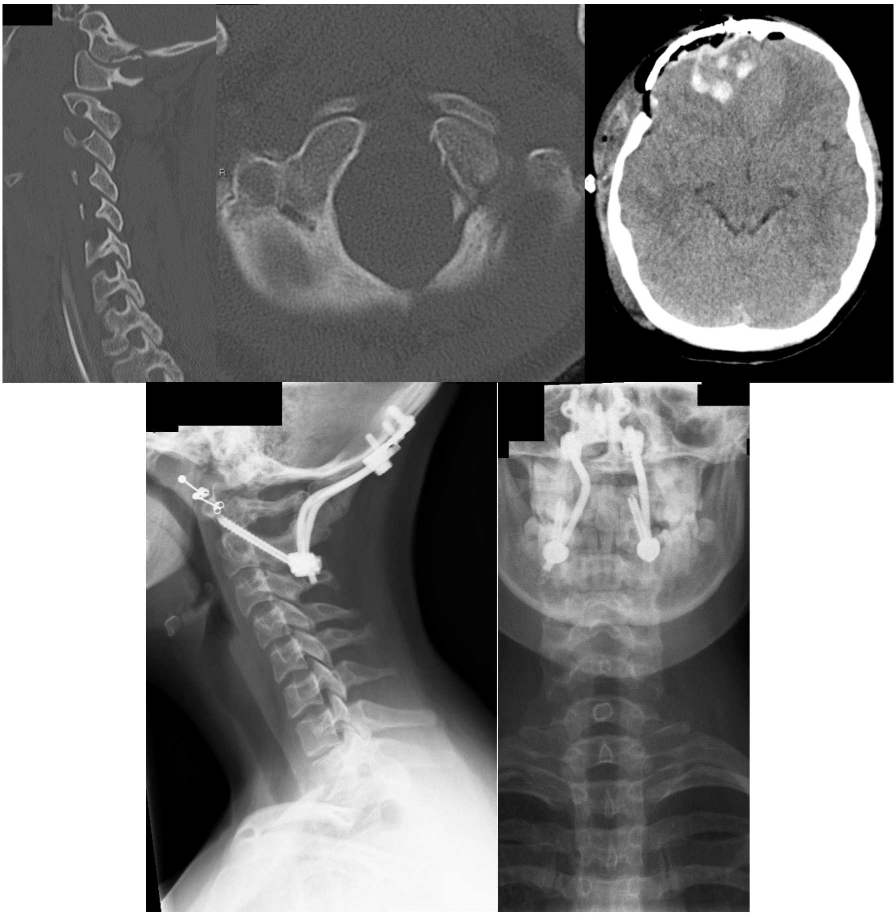

Figure 9. Instrumented cervical spinal fusion, OC fusion: Figs. 5-A to 5-D. 14-year-old girl. Preoperative cervical CT (A, B) demonstrates bilateral occiput fracture with C0-C1 instability. Preoperative scull CT (C) demonstrates skull fracture and epidural hematoma which were treated with craniotomy. Bilateral occiput fracture treated with posterior C0-C2 fusion. At two-year FU standing radiographs (D, E) demonstrate union.

Figure 10. Instrumented cervical spinal fusion, non-OC fusion: Figs. 6-A to 6-H. 10-year-old boy with C6-C7 rotational luxation and proximal thoracic scoliosis and type I neurofibromatosis. Preoperative cervical radiographs (A-C) and MRI (D) demonstrate C6-C7 rotational luxation and proximal thoracic scoliosis. Treated with posterior C1-Th9 fusion and decompression of C5-C6 to C7-Th1 and anterior C7 corpectomy. At three-year FU standing radiographs (E-H) demonstrate union, and patient participates in school physical education without symptoms.

5.4.1 OC spinal fusion vs. non-OC fusion

OC spinal fusion carried a higher risk of complication than non-OC fusions (60% (6/10) *vs* 24% (6/25); p = 0.043) (Table 10). Overall there were 11 different complications found on six patients observed in the children who underwent OC fusion, compared with the eight different complications on six patients who underwent non-OC spinal fusion. Implant failure was encountered in three children, who had rod breakage, all with OC fusion and over at least five vertebrae. Three children encountered non-union, all with OC fusion.

Table 10. Complications with OC and non-OC fusion (Study IV).

	OC-fusion (n=10)	Non-OC-fusion (n=25)	p-value
Complication (n)	6 (60%)	6 (24%)	0.043

5.4.2 Cervical spinal fusion before the age of ten years

The current series included 18 patients with the first instrumented cervical spinal fusion done before the age of ten and 17 children between the ages of 10 and 18. Complications were found more in children operated under the age of ten years than above (50% (9/18) *vs* 18% (3/17); p = 0.004) (Table 11).

Table 11. Complications in relation to Age (Study IV).

	Surgery before <10 yrs. age. (n=18)	Surgery at 10 to <18 yrs. age (n=17)	p-value
Complication (n)	9 (50%)	3 (18%)	<0.01

6 Discussion

6.1 Comparison with previous studies

The treatment of pediatric spine disorders is a broad field requiring consideration, experience and expertise. The Providence brace has previously been shown to be efficient with thoracolumbar and lumbar curves and has thus been recommended as the treatment for such (D´Amato et al. 2001, Yrjönen et al. 2006). However, thoracic curves are known to be in higher risk of progression (Ohrt-Nissen et al. 2016), especially in girls (Soucacos et al. 1998), and the publications and efficiency of the Providence brace in this group has thus far been modest. In D´Amato et al.´s study (D´Amato et al. 2001), which is the largest series on the Providence brace including 102 girls, the success rate with main thoracic curves was 43%. The treatment was considered successful if curve progression during FU was <5° and no surgery was needed. Yrjönen et al.´s study on the Providence brace did not include main thoracic curves, as their curve apex was at Th10 or below. When the curve apex is between T2 vertebrae and the T11-T12 disc space, scoliosis is counted as thoracic; when the apex is between T12-L1, it is counted as thoracolumbar; and when the apex is between L1-L2 disc space and L4-L5 disc space, the scoliosis is defined as lumbar according to the SRS definition (SRS 2000).

In the study by Ohrt-Nissen et al. (Ohrt-Nissen et al. 2016), including both thoracic and thoracolumbar curves, treatment success overall was 67% with the Providence brace but only 43% with main thoracic curves. Treatment success was defined as progression <5° during the study period. Thus, in that study, the results of the brace treatment were clearly different between curve types, and main thoracic curves had a higher risk of progression. In our study, the Providence brace was as efficient as in previous publications by D´Amato (2001) and Ohrt-Nissen (2016) with main thoracic curves, as 45% had no progression (<5°) during the follow-up. Skeletal maturity, age at the beginning of treatment and initial curve magnitude were similar in these three studies. The results of these three studies (D´Amato 2001, Ohrt-Nissen 2016, and the current study) are comparable, as all studies report the results as percentages, and Ohrt-Nissen (2016) and the current study also as medians. In terms of preventing the need for spinal fusion, curves ≥45° are to be considered for operative treatment (Mattila et al. 2013). In D´Amato (2001) study, 17% were operated, but this figure included all curve types, not only main thoracic. Furthermore, not all curves ≥45° are operated, but the proportion of patients that reached this limit in that study is not reported. In Ohrt-Nissen (2016) study, 33% reached this curve magnitude, but this figure also included all curve types, including thoracolumbar and lumbar curves. In the current study, 43% of the Providence brace treated patients reached a curve magnitude of ≥ 45°, which is a little higher than in previous publications by D´Amato (2001) and Ohrt-Nissen (2016). However, this can be explained by the fact that the current study included only main thoracic curves which are in a greater risk of progression than thoracolumbar and lumbar curves.

Different braces have been compared before. Katz et al. (Katz et al.1997) compared the Charleston night-time brace and the Boston brace and found the Boston brace overall more effective with a success rate of 66% vs 43% (Curve progression <6°), but their study included both thoracic and thoracolumbar curves. Janicki et al. study (Janicki et al. 2007), also including all curve types, compared the Providence brace with a TLSO brace, showing that the Providence brace was more effective in preventing curve progression when the initial curve at the beginning of treatment was ≤ 35°. The initial curve magnitude was shown to have a significant impact on treatment success, with better results by early treatment. These results indicate that practitioners should keep the spinal alignment in mind when treating and screening children, in hope of an early start of treatment when indicated.

We were unable to find previous studies comparing the Providence brace to the Boston brace in the treatment of main thoracic AIS, without other curve types. In the current study, the success rate for thoracic curves was equal between the Providence and the Boston Brace. Main curve progression to ≥45° and curve progression of >5° were similar between the brace alternatives. Initial curve magnitude was greater in the Providence group than in the Boston group, although the age at the beginning of treatment was the same. A possible cause for this was considered late referrals to treatment due to the lack of standardized AIS screening protocols in Denmark. The effect of this initial difference between the groups is unclear, as treatment efficiency was shown to be similar between the braces.

Albeit the majority of pediatric spinal disorders can be treated conservatively, instrumented spinal fusion, when indicated, can improve the outcome and quality of life. But it comes with a cost, since surgery is not without risks and is associated with the loss of mobility and a risk for deformity re-development and progression, i.e. distal adding-on, junctional scoliosis and PJK. Juvenile patients are at a risk because of their greater growth potential, and less research is done in this patient group with PSI. We found that PSI extended to the stable vertebra in JIS provides similar results compared with AIS fused to the touched vertebra. The longer fusion was not shown to have any negative effects on the HRQoL as measured by the SRS-24 questionnaire. Instead, the juvenile patients seemed to adapt better to spinal fusion done at an early age. Both groups showed an improvement in the SRS-24 scores for back pain, which is in line with a previous study (Sponseller et al. 2016) reporting on the benefits of operative treatment. However, like Sponseller et al. (2016), we found no correlation between improved SRS scores and radiographic deformity correction. They hypothesized that this was because all patients received good radiographic outcomes. In this study likewise both groups showed good correction which averaged over 75% in coronal correction. The correction was stable: There were no significant differences in the number of patients with distal adding-on between the groups despite the greater growth potential in JIS. In addition, the achieved alignment was equally sustained in both groups during FU. This is in line with Sponseller et al.´s (Sponseller et al. 2016) previous study, where extending the spinal fusion to at least the stable vertebra lead to only one (11%) patient of nine having deformity progression, as compared with 55% of those who were fused one level short of stable and had deformity progression during FU.

Understanding about the importance of sagittal balance is increasing (Schwab et al. 2013). The role of the instrumentation to sagittal alignment has been under discussion. Liu H et al. (Liu et al. 2015) noted that TK restoration is better with stiffer rods. This is in line with the findings of the current study (Study III), where reinforced rods provided better TK restoration than circular rods.

Ohrt-Nissen et al. (Ohrt-Nissen et al. 2017) were among the first to conduct a study on the impact of sagittal reinforced rods in AIS. In a study rather similar to ours, they had the best TK restoration with partial rail-range rods as compared with the full rail rods. They hypothesized that this was because with stiffer rods TK restoration can become technically more challenging in deformity surgery. Our findings in the reinforced rod group of a negative correlation between coronal curve correction and TK restoration, i.e. greater coronal correction had a negative effect on TK restoration, are in line with this hypothesis. We found this correlation to be true only with stiffer rods, not with circular rods. In line with this hypothesis and correlation, we consequently found the coronal correction in the reinforced rod group to be lower than in the circular rod group. However, with both rod alternatives, the coronal curve correction can be deemed as good.

Not all studies however have shown the impact of rods. Prince et al. (Prince et al. 2014) studied the effect of the rod diameter on sagittal balance restoration and found no effect. Their study of 352 AIS patients did not include CoCr rods but 5.5mm and 6.35mm rods of stainless steel, titanium and unknown rod materials. Monazzam et al. (Monazzam et al. 2013) did not find the rod material to influence the TK. They compared titanium, CoCr and stainless-steel rods on 280 AIS patients but used 5.5mm rods instead of 6.0 mm like in the current study.

Good alignment that is sustained for the rest of the patient’s life adds to HRQoL (Lafage et al. 2009). Previous studies have noted changes in the TK even after PSI

(Lamerain et al. 2014, Cheng et al.2005, Hwang et al. 2012a). To achieve sustained TK, stronger rods have been advocated (Liu et al. 2015). In the current study, no changes in TK, sagittal balance or coronal balance were noted during FU with any of the rods. This would indicate that both circular and sagittal reinforced 6.0mm CoCr rods seem to be stiff enough to sustain the achieved alignment and correction.

Patients with preoperative HK are at risk for HK even after PSI (Ohrt-Nissen et al. 2017, Fletcher et al. 2012). Ohrt-Nissen et al. (Ohrt-Nissen et al. 2017), using full reinforced rods, found an increased risk for postoperative HK as compared to partial reinforced rods and circular rods. Fletcher et al. (Fletcher et al. 2012), on the other hand, noted a smaller rod diameter to increase the risk for postoperative HK, but in their study, the rods with larger diameters were of stainless steel and the instrumentation used was not exclusively PSI. In the current study, the use of reinforced rods lowered the risk for HK during the two-year FU. Although there were only a few patients with HK in the entire study, better TK restoration in the reinforced rod group would imply that the use of reinforced rods would lower the risk for postoperative HK.

Although the operative technique was standardized, the circular rod group had more Smith-Peterson Osteotomies than the reinforced rod group (p=0.04). The reason for this is unclear, as the operative principles, deformity correction maneuvers and instrumentation were all standardized. However, the difference was small (less than one per patient), and as there exists no universal recommendations on the amount of osteotomies needed but these are instead done on the basis of individual surgeon preference, it is probable that this difference would not change the outcomes of the study.

The study (III) confirmed our hypothesis that stronger rods allowed for better sagittal balance restoration. However, maximal TK restoration with reinforced rods correlated with poorer coronal correction, which needs to be kept in mind when using reinforced rods in adolescents operated for idiopathic scoliosis. To keep this correlation in mind when conducting the deformity correction helps achieve best correction in all three planes, as the surgeon can thus try to find a balanced correction in all planes without the neglect of any plane. This is because both coronal and sagittal imbalance are reported to correlate with spinal disc degeneration (Bao et al. 2014) which can be a reason for a low HRQoL later on in life.

The anatomy and function of the cervical spine are different from the lower spine, which lends special features to the treatment of disorders in this portion of the spine. The course of vertebral artery through the vertebrae, the small size of the structures, and the close proximity and lack of mobility of the surrounding nerve structures make operative treatment of spinal disorders in this section of the spine more challenging. Hence, the indications and complications of instrumented spinal fusion in the cervical spine differ from those of the rest of the spine. Common indications in previous publications of instrumented spinal fusion in children are instability due to trauma (Kennedy et al. 2016), and congenital pathologies (Hwang et al. 2012b, Helenius et al. 2015). Likewise, in this series the indications for cervical spinal fusion were instability due to trauma or skeletal dysplasia. Operative techniques have evolved from previous semi-rigid wiring techniques towards rigid screw constructs, which in the lower spine have been shown to lower complication rates (Gluf et al. 2005, Hedeqvist et al. 2008, Helenius et al. 2015) and improve fusion rates (Gluf et al. 2005, Hedeqvist et al. 2008, Helenius et al. 2015). A more rigid fusion is thought to enable shortening or removing entirely the need for long postoperative external stabilization devices, such as a halowest. In this series likewise rigid fixation with screw constructs was the preferred method, wiring techniques were only used in two cases. One of these two patients experienced a tapping of the vertebral artery in an attempted C2 PS, which prevented the use of screws. The second patient was a 5-year-old boy with C1-2 instability and C0-2 stenosis and spondyloepiphyseal dysplasia, whose small size ruled out the use of screws.

The complication rate in this series (Study IV) was 34% with multiple complications in 11%, which is slightly higher than in previously published studies (Couture et al. 2010, Hwang et al. 2012b, and Odent et al. 2015). The reason for this is unclear, but likely due to the large number of skeletal dysplasia patients (66%). The quality and healing of the bone may be poorer in patients with skeletal dysplasia. Anatomic variations and different comorbidities that are sometimes present in syndromes can further increase the risk for complications. In the current study, complications tended to be slightly more prevalent in skeletal dysplasia patients than in trauma patients (39% vs 25% p=0.4), but this difference was not statistically significant.

The risk of complications in instrumented cervical spinal fusions is considerably higher than in AIS surgery of the lower spine, where a 2.5% complication rate in a group of 3217 patients has been reported (Bartley et al. 2017). In the current series of instrumented cervical spinal fusion, a higher risk was associated with OC (60%) fusion and fusion before the age of ten years (50%), compared with non-OC fusion (24%) and fusion at an older age (18%).

Previously, OC and non-OC spinal fusion has been shown to yield acceptable patient-reported results (Vedantam et al. 2017). Vedantam et al. measured the SRS-22 of 63 OC and 14 non-OC spinal fusion patients and found that the OC fusion SRS-22 scores were similar to those of AIS fusion patients. However, they did not compare the SRS-22 scores of OC fusions with non-OC fusions, and the complication rates were not published individually for the two groups.

OC fusion has been previously reported to be associated with a 14%-23% complication risk (Couture et al. 2010, Hwang et al. 2012b). The age of the child at operation is also a factor. In the study by Rajasekaran et al. (Rajasekaran et al. 2012) on pedicle screw safety, most of their pedicle screw breaches (67%) were found in patients under the age of ten years. In Odent et al.´s series (Odent et al. 2015) on 14 OC fusion patients, the only nonunion was encountered in a 2-year-old pediatric patient. They encountered an infection rate of 14%, nonunion rate of 7% and unintended fusion of the adjacent vertebra in 7% (Odent et al. 2015). The mean age in their series was 8 years, but the age of the other patients with complications was not specified, so the effect of age on the risk of complications in their study remains unclear.

In Couture et al.´s study (Couture et al. 2010) on 22 instrumented OC fusion patients, all encountered complications were found in patients operated before the age of ten years. However, the entire series consisted of young children with a mean age of 4.9 years. The correlation between age and complications was not estimated. In Hwang et al. (2012b) series on instrumented cervical spinal fusion of 912 adolescents, OC fusion was associated with a 14% complication rate, and an overall complication risk of 26% was observed. The average age at operation was 8.3 years. However, the outcome in the group of children operated under the age of ten was not recorded. Likewise, Gluf (Gluf et al. 2005) reported an overall complication rate of 10.4% in 67 children undergoing C1 to C2 fusion at a mean age of nine years, but the outcomes of children operated under the age of ten years was not reported. In cervical spine trauma, it is known that the incidence of spinal cord injury is higher in younger children than in older children (Carreon et al. 2004), as is the risk of death (Kokoska et al. 2001, Carreon et al. 2004).

However, in Vedantam et al.´s (Vedantam et al. 2017) study, older age was associated with poorer patient-reported outcomes. They hypothesized that this was because older children adapted less well to the decreased mobility of the cervical spine after fusion. This is in line with our findings (Study II) on JIS and AIS, where we also found the same difference. In Vedantam et al´s study, the effect of age on the risk of complications was not published and remains unknown.

The existing evidence indicates that cervical spinal fusion at a younger age carries a higher risk than spinal fusion at an older age. However, the small number of patients in many of the studies and the diverse etiologies and underlying comorbidities restrain this conclusion.

In the cervical spine, the fusion rate with rigid instrumentation has been good (Hedequist et al. 2009, Odent et al. 2015, Hwang et al. 2012b, Kennedy et al. 2016). In Hwang´s series (2012b), the overall fusion rate was 94.4%, with OC fusion rate of 99%. In Kennedy et al.´s (Kennedy et al. 2016) series on OC and non-OC spinal fusions, all did fuse. Their study on trauma and congenital pathologies included both screw and wiring techniques. In the current study three nonunions were noted, all were successfully treated with revision surgery and were fused at final FU. All the nonunions in this series took place in OC fusions.

The cervical spine is more prone to injuries than the lower spine, although the incidence of child cervical spine injury is rare (Kokoska et al. 2001). This is due to the child anatomy. The mortality rate in cervical spine injuries is higher than in injuries of the lower spine. Eleraky et al. (Eleraky et al. 2000) reported a mortality rate of 16% in 102 pediatric cervical spine injuries. The mortality rate in the current study (Study IV) was 14% with cervical spine trauma. The one trauma patient who died during the immediate postoperative period had a polytrauma, which is known to increase complication rates (Carreon et al. 2004).

6.2 Validity of the data

The retrospective design of these studies (Study I-IV) is a limitation. In Study I, the compliance data was not available in the Providence group, which is also a limitation. The patient-reported compliance in the Boston group was 60%. As the efficiency of the Providence brace in this study was better than in the literature published previously, and as compliance with a night-time brace is probably not inferior to a full-time brace, the efficiency of the Providence brace still compares favorably with the Boston brace. The brace selection was not randomized, and the outcome could have had more impact if the brace selection had been randomized. However, this study compared two groups of main thoracic AIS patients with similar age, gender, body mass index, menarchal status and treatment duration, which make the study populations comparable.

The two-year FU period (Study I-IV) is a relatively short time regarding the young age of these patients for all the long-term outcomes to be seen. This is true especially for the juvenile patients (Study II, III) who can still have growth remaining 2 years after PSI. In addition, the relatively small number of patients (Study III, IV) and the lack of 2-year FU information on all the patients in the reinforced rod group (Study III) are limitations (study III).

In our studies (Study II and III), the operation technique was the same for all the patients in different groups, and the same two experienced orthopedic spine surgeons performed and/or led all the operations. As a result, operation time and intraoperative blood loss were similar between the groups (Study II and III). In our study (Study II), the JIS group had more girls than the AIS groups ($p=0.027$), which can be due to earlier pubertal growth of girls and the fact that patients were as expected younger than in the AIS group ($p<0.001$). In the study III, the groups were also similar as comes to gender, age and total SRS-24 score. These factors make the results more comparable.

The diverse comorbidities and indications of surgery in the cervical spinal fusion group are also a limitation of our study (Study IV) but represent real life. All the patients in our study (Study IV) were operated by the same experienced orthopedic spine surgeon, which makes the operative techniques comparable while the diverse comorbities and indications as listed previously. The indications, outcomes and complications are carefully described, and none of the surviving patients were lost during FU.

7 Summary/Conclusions

This thesis work led to the following conclusions:

1. The Providence night-time brace is as effective as a Boston full-time brace in the conservative treatment of main thoracic AIS (I).
2. Posterior spinal fusion extended to the stable vertebra provides similar outcomes in JIS patients compared with AIS with fusion to the touched vertebra (II).
3. Both circular and sagittal reinforced 6.0mm CoCr rods provide adequate coronal and sagittal correction for adolescents operated for idiopathic scoliosis (III). The use of sagittal reinforced rods provides better restoration of thoracic kyphosis and may lower the risk for hypokyphosis (III).
4. Skeletal dysplasia associated with cervical instability and cervical spine injuries represented the most common indications for instrumented cervical spinal fusion in children (IV). Complications were observed in one-third of these children and 11% required revision surgery for complications (IV). OC spinal fusion and spinal fusion before the age of ten years were associated with a higher risk of surgical complications and mortality than non-OC fusions and cervical spinal fusions at an older age (IV).

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