Helsingin yliopisto (University of Helsinki)
Dissertationes Universitatis Helsingiensis
26/2023

Outcomes of Posterior Spinal Fusion in Pediatric Spinal Deformities

Eetu N. Suominen

ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Medicine of the University of Helsinki, for public examination in Töölö lecture hall, Meilahti Bridge Hospital, on 13 October 2023, at 12:00.

Helsinki 2023

University of Helsinki
Faculty of Medicine
Pediatric Surgery
Doctoral Programme in Clinical Research

Supervised by

Professor Ilkka Helenius
Department of Orthopaedics and Traumatology
University of Helsinki and Helsinki University Hospital
Helsinki, Finland

PhD Antti Saarinen
Department of Orthopaedics and Traumatology
University of Helsinki and Helsinki University Hospital
Helsinki, Finland

Reviewed by

Professor Ville Leinonen
Department of Neurosurgery
University of Eastern Finland
Kuopio, Finland

Associate Professor Joonas Sirola
Department of Orthopaedics, Traumatology and Hand Surgery
University of Eastern Finland
Kuopio, Finland

Opponent

Associate Professor Marko Neva
Department of Orthopaedics and Traumatology
Tampere University Hospital
Tampere, Finland

The Faculty of Medicine uses the Ouriginal system (plagiarism recognition) to examine all doctoral dissertations.

Publisher: Helsingin yliopisto
Series: Dissertationes Universitatis Helsingiensis 26/2023

ISBN 978-951-51-9088-8 (print)
ISBN 978-951-51-9089-5 (online)
ISSN 2954-2898 (print)
ISSN 2954-2952 (online)
PunaMusta, Joensuu 2023

To my family

Abstract

Pediatric spinal deformities encompass a wide range of conditions affecting the structural alignment and curvature of the spine. The most common pediatric spinal deformity is adolescent idiopathic scoliosis (AIS), a 3D deformity with lateral curvature of at least 10° diagnosed at the age between 10 and 18 years. Scheuermann's kyphosis is a spinal disorder that primarily affects the thoracic region. It is characterized an excessive front-to-back wedging of the vertebrae, leading to an increased thoracic kyphosis. Severe and progressing spinal curves are indications for surgical treatment. Posterior spinal fusion (PSF) with pedicle screws has become the golden standard for surgical treatment of pediatric spinal deformities.

This thesis aimed to study the outcomes of posterior spinal fusion in pediatric spinal deformities. We assessed the health-related quality of life (HRQoL) and radiographic outcomes of surgically treated adolescent Scheuermann's kyphosis patients and to compared it with healthy controls. We evaluated the complication and reoperation rates between AIS patients treated with PSF under two different intraoperative imaging techniques. We compared radiographic and HRQoL outcomes of two different designs of asymmetrical rods in AIS patients. We investigate the association between the HRQoL and Lenke classification as well as the extent of lumbar spinal fusion in AIS patients.

Posterior spinal fusion improves the HRQoL of Scheuermann's kyphosis patients during the 2-year follow-up. Intraoperative 3D imaging reduces pedicle screw-related complications and reoperations in AIS patients as compared with traditional 2D imaging. There were no differences in the coronal or sagittal deformity restoration in patients who underwent a posterior spinal fusion with sagittal reinforced rods and beam-like rods for AIS. Patients with major curve in the thoracolumbar area of spine had lower HRQoL as compared with patients having major curve in the thoracic spine. The extent of the lumbar spinal fusion had an association with lower HRQoL when lowest instrumented vertebra was at second lumbar vertebra or lower.

PSF with pedicle screw instrumentation results in good radiographic and HRQoL outcomes patients with Scheuermann's kyphosis and AIS. The current development of intraoperative imaging methods has an important role in reducing the pedicle screw-related reoperations and complications. The extent of PSF may have a predictive role in HRQoL outcomes during short- and long-term follow-up. Future studies should further evaluate methods to enhance thoracic kyphosis restoration. Whether the accuracy of pedicle screw placement can further be improved using robotics remains to be seen.

Tiivistelmä

Lasten selkärangan epämuodostumat kattavat laajan ryhmän selkärangan rakenteeseen vaikuttavia sairauksia. Yleisin lasten ja nuorten selkärangan epämuodostumasairaus on nuoruusiän idiopaattinen skolioosi (adolescent idiopathic scoliosis, AIS), jossa selkärangan sivuttaissuuntainen kaarevuus on edestäpäin otetussa röntgenkuvassa vähintään 10°. Scheuermannin taudissa korostuu rintarangan voimakas kuperuus taaksepäin. Posteriorinen selän luudutusleikkaus pedikkeliruuvi-instrumentaatiolla on nykyisin eniten käytetty menetelmä lasten selkärangan epämuodostumasairauksien kirurgisessa hoidossa.

Väitöstutkimuksen tarkoituksena oli tutkia selkärangan posteriorisen luudutusleikkauksen lopputuloksia nuoruusiän idiopaattista skolioosia ja Scheuermannin kyfoosia sairastavilla potilailla. Arvioimme leikkauksen vaikutusta terveyteen liittyvään elämänlaatuun Scheuermannin kyfoosissa sekä vertasimme sitä terveisiin, samanikäisiin verrokkeihin. Vertasimme skolioosileikkauksessa asennetuista pedikkeliruuveista aiheutuneiden komplikaatioiden ja uusintaleikkauksien määrää 2D- ja 3D-kuvantamistekniikan välillä. Vertasimme rintarangan kyfoosin korjaantumista kahden erilaisen leikkausinstrumentaation välillä AIS-potilailla. Lisäksi selvitimme elämänlaadun ja posteriorisen luudutusleikkauksen laajuuden välistä yhteyttä.

Posteriorinen luudutusleikkaus paransi Scheuermannin kyfoosipotilaiden elämänlaatua kahden vuoden seuranta-aikana. Leikkauksen aikainen 3D-kuvantaminen vähensi pedikkeliruuveihin liittyviä komplikaatioita ja uusintaleikkauksia verrattuna 2D-kuvantamiseen. Ratakiskoprofiilin tangot eivät parantaneet rintarangan kaarevuuden korjaantumista AIS-potilailla verrattuna sagittaalisesti vahvistettuihin tankoihin. Potilailla, joilla skolioosin pääkäyryys sijaitsi lannerangan alueella, oli leikkauksen jälkeen huonompi terveyteen liittyvä elämänlaatu kuin potilailla, joilla pääkäyryys oli rintarangan alueella. Lisäksi luudutusleikkaus laski potilaiden elämänlaatua, mikäli se ulottui toiseen lannenikamaan tai alemmas.

Posteriorisella selän luudutusleikkauksella pedikkeliruuvein parantaa potilaiden elämänlaatua. Leikkauksen aikaisten kuvausmenetelmien kehityksellä on merkitystä ruuvikomplikaatioiden ja uusintaleikkausten määrän vähentämisessä. Luudutusleikkauksen laajuudella saattaa olla elämänlaatuun liittyvää ennustearvoa lyhyen ja pitkän aikavälin seurannassa.

List of Abbreviations

95%CI	95% confidence interval
AIS	Adolescent idiopathic scoliosis
ASF	Anterior spinal fusion
BLR	Beam-like rod
CSVL	Central sacral vertical line
CT	Computed tomography
FU	Follow-up
HRI	Harrington Rod Instrumentation
HRQoL	Health-related quality of life
LIV	Lowest instrumented vertebra
LL	Lumbar lordosis
MEP	Motor evoked potential
PI	Pelvic incidence
PSF	Posterior spinal fusion
PS	Pedicle screw
PSI	Pedicle screw instrumentation
SD	Standard deviation
SK	Scheuermann's kyphosis
SRR	Sagittal reinforced rod
SRS-24	The Scoliosis Research Society 24-item questionnaire
SVA	Sagittal vertical axis
TK	Thoracic kyphosis

Table of Contents

List of Original Publications

This thesis is based on the following publications:

I. Suominen, E.N., Saarinen, A.J., Syvänen, J., Diarbakerli, E., Helenius, L., Gerdhem, P., & Helenius, I. (2022). Health-related quality of life outcomes in adolescent Scheuermann's kyphosis patients treated with posterior spinal fusion: A comparison with age-and sex-matched controls. *Journal of Children's Orthopaedics*, *16*(4), 290-296.

II. Saarinen, A.J., Suominen, E.N., Helenius, L., Syvänen, J., Raitio, A., & Helenius, I. (2022). Intraoperative 3D imaging reduces pedicle screw related complications and reoperations in adolescents undergoing posterior spinal fusion for idiopathic scoliosis: a retrospective study. *Children*, *9*(8), 1129.

III. Suominen, E.N., Saarinen, A.J., Syvänen, J., Ahonen, M., Helenius, L., & Helenius, I. (2022). Beam-Like rods do not Provide Additional Improvement to Thoracic Kyphosis Restoration when Compared to Sagittal Reinforced rods in Adolescents Undergoing Spinal Fusion with Pedicle Screw Instrumentation for Idiopathic Scoliosis. *World Neurosurgery*, *168*, e555-e561.

IV. Frantzén, A., Suominen, E.N., Saarinen, A.J., Ponkilainen, V., Syvänen, J., Helenius, L., Ahonen, M., & Helenius, I. (2023). Association between Lenke Classification, The Extent of Lumbar Spinal Fusion, and Health-Related Quality of Life after Instrumented Spinal Fusion for Adolescent Idiopathic Scoliosis. *Submitted for publication*.

The publications are referred to in the text by their roman numerals.

1 Introduction

Spinal deformities can be present in patients in all age groups. In pediatric patients, the deformities result from congenital anomalies, genetic conditions, neuromuscular disorders, connective tissue disorders (e.g. Marfan syndrome), neurofibromatosis, skeletal dysplasia or idiopathic (Wiggins et al., 2003). The most common structural form of pediatric spinal deformity is adolescent idiopathic scoliosis (AIS), characterized by lateral curvature of at least 10° as measured from coronal radiographs using the Cobb technique at the age between 10 and 18 years (Weinstein et al., 2008). Other pediatric spinal deformities include early onset scoliosis, neuromuscular scoliosis, and Scheuermann's kyphosis (SK). In spondylolysis and spondylolisthesis, the deformities can be present as anteriorly shifted or slipped vertebrae.

Pathoanatomic factors and pathophysiology in spinal deformities define the typical clinical and radiographic characteristics of each disorder. Deformities can be present in coronal, sagittal, and/or axial planes. The terms scoliosis, kyphosis, and lordosis are used to describe the curvatures of the spine, and to refer to abnormal dimensions from normal spinal alignment (Deacon et al., 1987; Dickson, 1988). Scoliosis is defined as the spinal curvature in the coronal plane, while kyphosis and lordosis refer to sagittal curvature in the thoracic and lumbar spine, respectively. Furthermore, the vertebrae can be rotated around their longitudinal axis. Scientific research has helped to understand the three-dimensional nature of AIS, which is often involved with thoracic hypokyphosis or reduced lumbar lordosis and with axial rotation in the horizontal plane (Labrom et al., 2021).

Conservative approaches in the treatment of pediatric spinal deformities include observation and monitoring, bracing, casting, and physical therapy (Lonstein & Winter, 1994; Olafsson et al., 1995). The effectiveness of conservative methods depends on the severity and progressive nature of the condition, the type and degree of the curvature, and the age of the patient (Kaelin, 2020; Rowe et al., 1997). Bracing and casting of the spine aim to correct the deformity with natural growth. Severe deformity, progressive nature of the deformity, neurological deficits, compromised cardiopulmonary function, poor cosmetics, and persistent pain are indications for surgical intervention.

Prevention of the curve progression and improvement of the coronal and sagittal balance are the primary goals in spinal deformity surgery. Furthermore, the surgical treatment improves patient-reported health-related quality of life (HRQoL) and alleviates pain and deformity (Ahonen et al., 2023; Helenius et al., 2019). The short, mid, and long-term outcomes after posterior corrective surgery can be described in several ways. Patient-

reported outcome measures allow the evaluation of changes in patient's quality of life and function. Radiographic outcomes can be assessed in terms of coronal and sagittal plane correction, as well as sagittal balance and alignment. Assessing the rates of complications and reoperations is important when the possible risks are balanced with potential benefits of the surgical procedures.

When compared with traditional spinal deformity surgery, modern surgical techniques and all-pedicle screw instrumentation systems have resulted in better deformity correction in coronal, axial, and sagittal planes while the complication rates have not increased (Ledonio et al., 2011). Pedicle screw instrumentation (PSI) as a posterior corrective surgical technique allows effective, three-dimensional correction of the spinal deformity (Mattila et al., 2013; Suk et al., 1995). In this method, the spine is instrumented bilaterally using pedicle screws (PS) and these are connected with rods, which allows three-dimensional correction of the deformity and prevents the curve from progression. This technique represents nowadays the golden standard method in AIS surgery and is applied also in the surgical treatment of Scheuermann's kyphosis, spondylolisthesis, and spinal fractures.

This thesis focuses on the outcomes in the surgical treatment of pediatric spinal deformities. Patients in this thesis were diagnosed either with SK or with AIS. This thesis aims to compare the HRQoL of operatively treated SK patients with healthy controls and to study the association between the HRQoL and Lenke classification in AIS patients. Furthermore, the aims are to compare the pedicle screw-related complications and reoperation rates between two different intraoperative imaging methods and the correction of sagittal balance between two different instrumentation types in AIS patients.

2 Review of the Literature

2.1 Adolescent idiopathic scoliosis

Adolescent idiopathic scoliosis (AIS) is a complex 3D structural disorder of the spine seen in children from 10 years old until skeletal maturity. According to the traditional classification based on the age of onset, idiopathic scoliosis can be divided into infantile (0-3 years), juvenile (3-10 years), and adolescent idiopathic scoliosis, of which the AIS is far most common (Horne et al., 2014; Weinstein et al., 2008). Idiopathic scoliosis features a structural, lateral curvature of the spine greater than 10 degrees as measured with the Cobb technique on standing coronal radiography and is typically associated with trunk rotation (Figure 1) (Cobb, 1948). Furthermore, the condition is often associated with a reduction in thoracic kyphosis (i.e. hypokyphosis) (Clément et al., 2013).

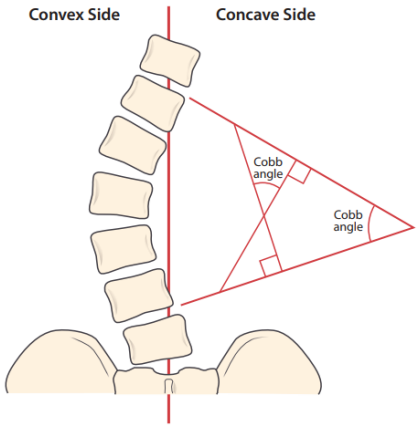

Figure 1 The Cobb technique. The scoliotic curvature is defined as the angle between the upper border of the upper vertebra and the lower borders of the lowest vertebra (Cobb, 1948).

When the lower limit of 10 degrees of lateral curvature in the spine is used as a diagnostic criterion, approximately 1 to 3% of the adolescent (children between 10 and 16 years) have

scoliosis, but only 0.3% to 0.5% have curves greater than 20° (Weinstein et al., 2008). Females are more often affected than males, and also have a higher incidence for greater curve magnitudes (Luk et al., 2010; Ueno et al., 2011). Curves greater than 30° affect females 10 times more often than males (Weinstein, 1989).

Most patients are initially present because of an asymmetry in the shoulders, waist, or gait noticed by parents or in screening exams, rather than clinical symptoms. Physical examination for scoliosis consists of the Adam's forward bend test and neurological examination of the lower extremities. In the primary examination, a scoliometer can be used to estimate the degree of the rotational asymmetry (Figure 2). The scoliotic curve causes spinal rotation resulting in a rib hump, which in 85% to 90% of cases is located on the right thoracic area (Horne et al., 2014). As the pathogenesis of AIS is not fully understood, the diagnosis is not made until non-idiopathic (i.e., congenital, neuromuscular, neural, or syndromic) causes of scoliosis have been excluded. Therefore, a full neurological and musculoskeletal examination is necessary. Several red flag signs need to be recognized. These include severe back pain, night-time back pain neurological disorders, and thoracic scoliosis convex to the left (Horne et al., 2014).

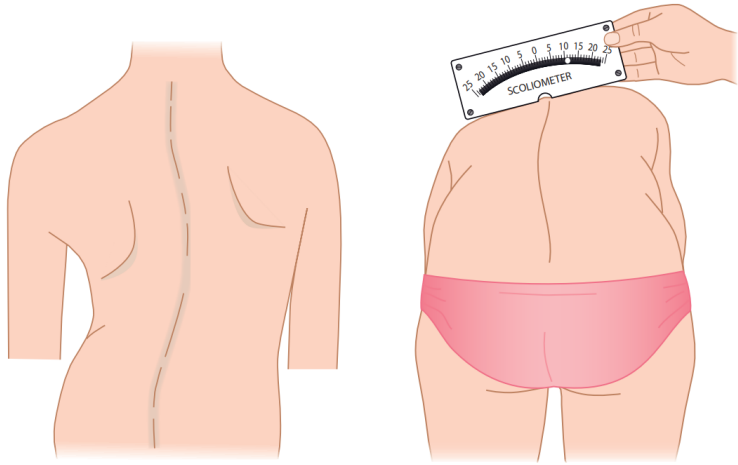

Figure 2 Scoliosis is characterized with an abnormal lateral curvature of the spine. The most common clinical signs include asymmetry in the shoulders, waist, and/or gait. Scoliometer can be used when investigating the vertebral rotation and rib humping.

To assess the degree of scoliosis, full-length posteroanterior and lateral spinal standing radiographs including pelvic area should be used. On a plain posteroanterior radiograph, the magnitude of the scoliosis curve is determined with the Cobb technique (Cobb, 1948). Lateral radiographs are used to assess sagittal balance. Lateral bending radiographs are taken if surgery is considered and provide information on curve flexibility. Magnetic resonance imaging (MRI) is indicated in patients with very rapid curve progression, back

pain, or neurological deficits. Preoperatively, a pulmonary function test should be performed (Newton et al., 2005).

2.1.1 Radiographic parameters of the spinal balance

Pediatric spinal deformities can affect the spinal balance in coronal, horizontal, and sagittal planes. The concepts and parameters of spinal balance are therefore critical to the evaluation of spinal deformity.

Coronal imbalance is a type of spinal deformity with deviation from the midline in the coronal plane. The radiographic assessment of spinal scoliosis can be performed as a vertical line drawn downwards from the mid-point of the C7 vertebral body. The horizontal distance between this line and the midline of the sacrum (central sacral vertical line, CSVL) is measured. Coronal balance is interpreted as neutral if the plumb line is within 20 mm of the CSVL. Vertebrae bisected by the center sacral line are designated as the "stable" vertebrae; this feature is applied in the design of the spinal fusion surgery.

Three consecutive curvatures from cranial to caudal can be recognized in the sagittal profile: cervical lordosis (CL), thoracic kyphosis (TK), and lumbar lordosis (LL). Normal thoracic kyphosis, measured from T5 to T12, has been described to be approximately 20° to 40° (de Jonge et al., 2002). The sagittal vertical axis (SVA) corresponds to the horizontal distance between a vertical line drawn downwards from the centrum of the C7 vertebral body and the posterior–superior corner of the first sacral vertebra (S1) (Figure 3).

In addition, several pelvic parameters which affect the sagittal balance can be defined. The pelvic tilt (PT) is defined by the angle created by a line running from the sacral endplate midpoint to the center of the bifemoral heads and the vertical axis. It illustrates the rotation of the pelvis around the femoral heads. The sacral slope (SS) is defined by the angle between a line tangent to the upper endplate of the first sacral vertebra and the horizontal line. It characterizes the position of the S1 endplate. The pelvic incidence (PI) is defined as an angle between the perpendicular to the upper S1 level passing through its center and the line connecting this point to the axis of the femoral heads (Duval-Beaupère et al., 1992). PI is the only parameter that is anatomically fixed after adolescence. It can be described as a sum of sacral slope and pelvic tilt.

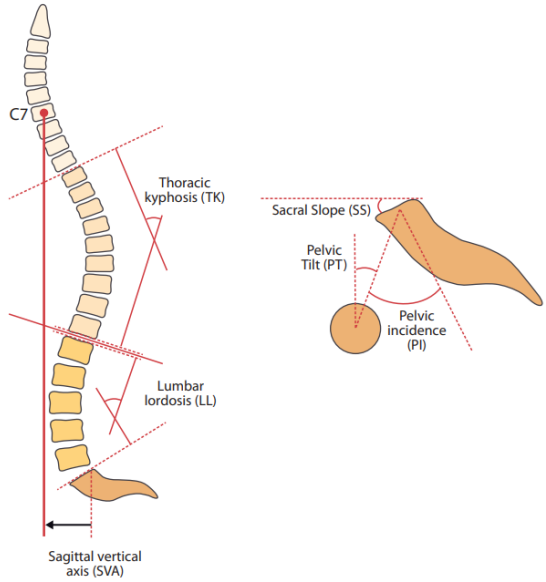

Figure 3 Sagittal balance parameters of spine and pelvis.

2.1.2 Classification systems of AIS

Several classification systems have been developed for AIS. Cobb first gave a description of major and minor curves as well as structural and non-structural curves (Cobb, 1948). Structural curves are fixed, nonflexible, and fail to correct with bending, while nonstructural curves are flexible and readily corrected with bending. Curve type and location remain important parts also in modern classification systems but have been supplemented with advanced features. King and Moe published one of the most widely recognized classifications for AIS in 1983 (King et al., 1983). The King classification aimed to guide treatment decisions to preserve as much motion in the operated spine as possible (King et al., 1983). The development of the King-Moe classification system was based on surgical treatment experience with Harrington rod instrumentation (HRI) and provided a basis for selective spinal fusion. The categorization of curves was based on the coronal plane but did not include thoracolumbar, lumbar, double major, or triple major curves. Furthermore, the sagittal alignment was not considered. As the segmental hybrid and pedicle screw instrumentation systems in AIS surgery became more popular, the King-Moe classification system was outdated to give accurate guidelines and recommendations for which spinal levels should be instrumented.

The Lenke classification system was published in 2001 and overcame several limitations of the King-Moe system (Lenke et al., 2001). The Lenke classification is based on coronal and sagittal planes and aims to give guidelines on which vertebral levels are appropriate in

spinal fusion. It includes six curve types numbered from 1 to 6 as follows: main thoracic, double thoracic, double major, triple major, thoracolumbar/lumbar, and thoracolumbar/lumbar-main thoracic. Proximal thoracic, main thoracic, and thoracolumbar-lumbar are divided into structural and non-structural curves. The structural curves lack normal, objectively estimated flexibility with Cobb angle in lateral bending radiographs greater than 25°. Upper thoracic kyphosis (T2-T5 >20°) and thoracolumbar kyphosis (T10-L2 >20°) indicate additional structural criteria in the sagittal plane. In the Lenke classification, lumbar and thoracic sagittal modifiers are added to the basic curves (Table 1).

Table 1 The Lenke classification system for AIS.

Type	Proximal thoracic (PT)	Main thoracic (MT)	Thoracolumbar/ Lumbar (TL/L)	Curve type
1	Non-Structural	Structural	Non-Structural	Main Thoracic (MT)
2	Structural	Structural	Non-Structural	Double Thoracic (DT)
3	Non-Structural	Structural	Structural	Double Major (DM)
4	Structural	Structural	Structural	Triple Major (TM)
5	Non-Structural	Non-Structural	Structural	Thoracolumbar/Lumbar (TL/L)
6	Non-Structural	Structural	Structural	Thoracolumbar/Lumbar – Main Thoracic (TL/L-MT)
Modifiers				
Lumbar Spine Modifier	**CSVL to Lumbar Apex**		**Thoracic Sagittal Modifier**	**Thoracic Kyphosis T5-T12**
A	CSVL between pedicles		-	< 10°
B	CSVL touches apical body/bodies		N	10-40°
C	CSVL completely medial		+	> 40°

The lumbar modifiers are defined as the location of the CSVL on the apical vertebra of the lumbar curve. A stable vertebra is defined as the vertebra most proximally bisected by the CSVL. In the Lenke classification, three lumbar modifiers are defined. If the CSVL runs between the lumbar pedicles, modifier A is used. If the CSVL runs between the medial border of the lumbar concave pedicle and the lateral margin of the apical vertebral body, modifier B is used. Modifier C is used if the CSVL falls medial to the lateral aspect of the lumbar apical vertebral body.

The sagittal thoracic modifiers depend on the magnitude of the thoracic kyphosis on levels T5-T12. Modifier (–) is used if the patient's thoracic kyphosis is less than 10° (i.e. hypokyphosis), modifier (N) if the TK is 10°- 40° (i.e. normal), and modifier (+) if the TK is greater than 40° (i.e. hyperkyphosis).

2.1.3 Natural history of AIS

The research on the natural history of AIS is limited. Based on the Iowa natural history cohort, patients with untreated AIS can function well as adults, as estimated in terms of employment, marriage status, and having children (Weinstein, 2019). The evidence also suggests that AIS less than 70° does not result in increased mortality (Pehrsson et al., 1992; Danielsson, 2013). Curve progression is the most important factor in the natural history of idiopathic scoliosis, and the majority of major curves measuring between 50° and 75° at maturity, especially thoracic curves, have significantly increased likelihood for progression (Danielsson, 2013; Weinstein et al., 1981). Untreated scoliosis may lead to increased back pain and pulmonary symptoms for patients with large thoracic curves (Weinstein, 2019). Increasing thoracic scoliosis is associated with decreasing pulmonary function in patients with adolescent idiopathic scoliosis when compared with age, sex, and height-matched controls (Newton et al., 2005). As pulmonary function is considered to peak at the age of 20, the natural decline of pulmonary function causes extra burden to those who already have reduced function in early adulthood. Scoliosis has a negative effect also on a patient's self-image and cause dissatisfaction with physical appearance (Rushton & Grevitt, 2013a). AIS patients with a single MT curve maintain equal HRQoL status compared with healthy controls. Patients with structural TL/L curves are likely to experience greater annual TL/L curve progression and have substantial low back pain or worse low back pain-specific HRQoL status during middle age (Watanabe et al., 2020). Depending on the patient's skeletal maturity and the curve severity, a choice is made between observation and conservative or surgical treatment of AIS. In patients with curves less than 25°, observation is recommended.

2.1.4 Brace treatment in AIS

For skeletally immature AIS patients with curves between 25° to 45°, bracing (i.e., thoraco-lumbo-sacral orthosis, TLSO) as a primary therapy is considered to prevent the curve progression until skeletal maturity is reached. The brace treatment is the only non-operative method proven to halt the curve progression in scoliosis. There is a higher success rate when compared to observation only with results being directly related to compliance with brace treatment. A brace applies external force to the trunk during the patient's growth phase to prevent scoliosis progression. There are several different brace designs, including full-time Boston and Wilmington TLSOs and nighttime Providence or Charleston braces (Kaelin, 2020). Some brace designs, such as the Milwaukee brace, include the cervical area for treatment of thoracic and double curves (i.e., cervico-thoraco-lumbo-sacral orthosis, CTLSO).

A success rate of 74% for underarm plastic bracing after four years of follow-up, and a 34% success rate for observation only has been reported (Nachemson & Peterson, 1995). Results are supported by a meta-analysis by Rowe et al. who also compared the efficiency

of bracing between 8, 16, and 23 h per day (Rowe et al., 1997). Increasing brace-wearing time is associated with a progressively higher success rate (Rowe et al., 1997). A randomized clinical trial by Weinstein et al showed a decreased progression of high-risk curves to the threshold of surgery in AIS patients (Weinstein et al., 2013). Although bracing is an effective treatment method for preventing scoliosis from progressing, it can be psychologically difficult (Matsunaga et al., 2005; Tones et al., 2006). Poor compliance with brace wearing has been reported especially among male patients (Karol, 2001; Yrjönen et al., 2007).

2.2 Scheuermann's kyphosis

Dr. Holger Scheuermann first described an association between juvenile thoracic kyphosis and vertebral body changes in 1920 (Scheuermann, 1977). Scheuermann stated on basis of radiographs that the condition results from anterior wedging of the thoracic vertebrae. Sorenson later introduced the criteria for diagnosis of Scheuermann's kyphosis (SK, also known in the literature as Scheuermann´s disease) (Sorenson, 1964). SK is characterized by anterior wedging of greater than or equal to 5º in three or more adjacent vertebral bodies (Figure 4). Other radiographic findings include irregularity of the vertebral endplates and intraosseous disk herniation (Schmorl's node) (Palazzo et al., 2014). The incidence of Scheuermann's has been estimated to range from 0.4 to 10% (Bradford et al., 1974; Damborg et al., 2006). The exact etiology of SK remains unclear. Different theories include genetic etiology, increased levels of growth hormone, and the influence of increased mechanical stress (Aufdermaur, 1981; Damborg et al., 2006; van Linthoudt & Revel, 1994).

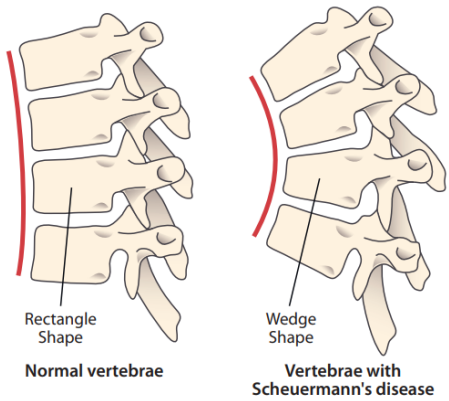

Figure 4 The Scheuermann's kyphosis is characterized by greater than 5° anterior wedging of at least three consecutive vertebrae.

The classical form of Scheuermann's disease is characterized by dorsal kyphosis, which is often painful and fixed (Figure 5) (Scheuermann, 1977). The dorsal kyphosis in the thoracic spine leads to a compensatory, non-structural hyperlordosis of the lumbar spine. Other changes in the posture include anteversion of the pelvis, rounding of the shoulders, and the head in forward protrusion (gooseneck). Thoracolumbar and lumbar forms of the SK have also been described. Thoracolumbar form is characterized by the apex of the kyphosis at levels T11-T12, and lumbar form with loss of the LL (Edgren & Vainio, 1957). In contrast to AIS which has a higher prevalence among females, in SK the female-to-male ratio is close to one (Ali et al., 1999).

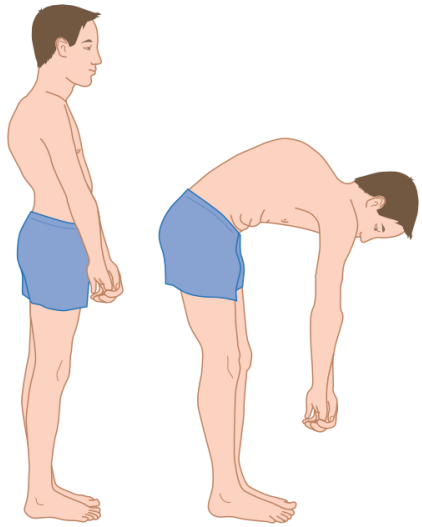

Figure 5 The most typical clinical characteristic in Scheuermann's kyphosis is a postural deformity or "hunchbacked" appearance.

2.2.1 Natural history of Scheuermann's kyphosis

There is limited research on the natural history of SK. In most cases, the natural course is benign with no severe disability after the completion of spinal growth. However, an increased prevalence of back pain has been associated with SK, and at least in the classical thoracic form of SK, there appears to be a higher likelihood for back pain (Murray et al., 1993; Ristolainen et al., 2012). Murray et al reported in their 32-year follow-up study that patients with SK experience more thoracic pain than healthy controls (Murray et al., 1993). However, no difference in the need for pain medication, sick leave due to back pain, and restriction of activities of daily living were found. In the 37-year follow-up study of Ristolainen et al, the prevalence of back pain was 39% in SK patients, which was 2.5 times

higher than in the healthy control group. There is a higher risk for the development of restrictive lung disease only if the kyphosis exceeds 100° (Murray et al., 1993).

2.2.2 Conservative and brace treatment of SK

The selection of the treatment methods depends on the severity of the pain as well as on the degree and progression of the kyphotic deformity. First-line treatments are physiotherapy and bracing. Different exercises including hamstring stretching and trunk extensor strengthening demonstrate a positive effect on back pain (Weiss et al., 2002). In skeletally immature SK patients with 45° to 65° thoracic kyphosis, bracing is widely recognized as an effective treatment method. The brace worn time should be from 16 to 23 hours a day for 18 months. After this, part-time wearing should be continued for an additional 18 months with gradual withdrawal (Montgomery & Erwin, 1981; Sachs et al., 1987). Like AIS, different types of braces have been used in the treatment of SK.

In the brace treatment of SK, extension braces are used. They consist of one posterior support at the apex of the TK and two compensatory anterior supports. Bradford et al. reported a 40% decrease in mean TK and a 35% decrease in mean LL after an average of 34 months of use of the Milwaukee brace (Bradford et al., 1974). Gutowski and Renshaw compared the results of Boston and Milwaukee bracing and found out that SK patients had an average improvement in kyphosis of 27% in the Boston group and 35% in the Milwaukee group, despite the use of the Milwaukee brace for older patients who had greater curves (Gutowski & Renshaw, 1988). After a 5-year follow-up in 100 SK patients treated with consistent bracing, 76 of the patients who wore the brace consistently showed improvement in the TK when compared to the pretreatment, while 24 showed worsening and 10 were unchanged (Sachs et al., 1987).

2.3 Surgical treatment of pediatric spinal deformities

The indications for surgery in AIS are curves greater than 45° to 50° and/or rapidly progressing curves (Hresko, 2013; Weinstein et al., 2008). The indications for the surgical treatment of Scheuermann's kyphosis are a stiff and symptomatic thoracic kyphosis with a curve greater than 75° after a failure of conservative treatment (Tsirikos & Carter, 2021). The goals of surgery are to obtain good correction of the spinal deformity, prevent curve progression, improve health-related quality of life, prevent back pain, and preserve function while postponing degenerative changes.

2.3.1 Evolution of surgical instrumentation in AIS surgery

Surgical treatment of AIS has been under continuous evolution during the last century. The earliest descriptions of surgical treatment of spinal deformities are from Dr. John Hibbs in

1911 (Ra, 1911). It was not until 1924 that he described the surgical technique, which applied cast correction and spinal fusion. The early era of AIS surgery was characterized by poor deformity correction and challenged by a high incidence of pseudoarthrosis, other complications, and a high rate of reoperations. The earliest methods relied on fusion of the spinal levels without any supporting instrumentation. Prolonged bed rest in a body cast followed the surgical treatment.

Harrington rod instrumentation was developed in the 1950s and soon revolutionized the surgical treatment of AIS (Harrington, 1962). Harrington rods are characterized by proximal and distal anchors or hooks, which provide distraction on the concave side of the scoliotic deformity. HRI was designed to apply distractive forces via a single rod with ratchets on one end in combination with a single hook at each end of the rod. Therefore, it had no effects on spinal rotation. Postoperative immobilization was needed to prevent dislodgement of the hooks. From the early 1960s to the early 1980s, the HRI was considered a standard of care in the treatment of AIS. Decades later, studies showed that the combination of a straight rod and distractive forces caused a loss of TK as well as LL, which further caused anterior translation of the vertical axis and the body's overall poor sagittal spinal balance (Cochran et al., 1983; Dickson et al., 1990). This type of sagittal imbalance with associated symptoms is called "flatback syndrome".

To improve the three-dimensional correction of the deformity and permit the application of selective distraction and compression, Cotrel and Dubousset introduced segmental hook instrumentation in the 1980s (Cotrel & Dubousset, 1984). This changed the treatment from concave distraction to segmental realignment and made rod rotation maneuvers and cantilever methods possible (Cotrel et al., 1988; Webb et al., 1995). The King-Moe classification provided the basis for the selective fusion with Cotrel and Dubousset (CD) instrumentation (King et al., 1983). With CD instrumentation, better long-term functional and radiographic outcomes in AIS patients can be achieved when compared with HRI (Helenius et al., 2003). However, complications were more common in CD instrumentation. The original CD instrumentation, which was based on hook systems, was later modified with segmental pedicle screw constructs, and became a gold standard in posterior spinal fusion. Suk published his results of posterior transpedicular fixation using all pedicle screw constructs in 1995 (Suk et al., 1995).

The advanced properties of pedicle screws include excellent deformity correction, shorter fusion, and less operation time (Halm et al., 2000; Hamill et al., 1996). When compared with hybrid instrumentation, all-pedicle screw constructs provide better maintenance of corrective parameters with exception of global sagittal balance (Crawford et al., 2013). One of the most important properties of pedicle screws compared to hook and hybrid instrumentation is that they are anchored in the dense bone of the pedicles. This enables rigid internal immobilization and provides stronger fixation compared to other types of spinal instrumentation. In hooks or wire systems, the axis of fixation is posterior to that of vertebral rotation, which does not enable sufficient force for vertebral rotation. However,

with pedicle screws, the internal fixation provides sufficient torque to also correct the rotational deformity.

2.3.2 Posterior spinal fusion with pedicle screw instrumentation in AIS

Posterior spinal fusion with pedicle screws has since become the golden standard for surgical treatment of all curve types of AIS. The specific details of the procedure may vary depending on the individual patient and the severity of the condition. The anterior approach has special indications in complex and severe deformities in AIS. These include the need to increase the flexibility of rigid curves (anterior discectomy and release), arrest vertebral growth in skeletally immature patients, and reduce the number of fusion levels (Sud & Tsirikos, 2013).

In the planning of the AIS surgery, the decision of which curves are included in the fusion is made. Currently, the selection of fusion levels is based on the Lenke classification system (Lenke et al., 2001). Each Lenke curve type has characteristic areas, which according to the guidelines should undergo fusion. Other factors used to determine the length of fusion include the patient's lifestyle, activity level, and preference for sports. In general, structural curves should be included in the fusion. In Lenke curves 1C and 2C as well as some 3C and 4C, which are characterized by a lumbar compensatory curve, a decision of selective fusion is made. Selective fusion is based on the fact that spontaneous correction of the flexible compensatory lumbar curve is possible after the thoracic fusion (Edwards et al., 2004; Ritzman et al., 2008). Selective fusion may therefore save motion segments, which is especially important in the lumbar spine. In curve types with structural thoracolumbar/lumbar curves (i.e. types 3, 4, 5, and 6) the selection of the lowest instrumented vertebra (LIV) is influenced by the relationship of the lumbar curve to the CSVL, the flexibility of the disk caudal to the proposed LIV, and axial plane rotation and flexibility (Trobisch et al., 2013).

In the surgery, the muscles and other soft tissue are moved aside subperiostally to expose the spine along the fusion length. In pedicle screw fixation, pedicle screws are inserted into the vertebral column in a multisegmental procedure at the length of an intended fusion (Suk et al., 2012). Presumed entry points are decorticated and guide pins are inserted along the axis of the pedicle. After a radiographic confirmation of the ideal pedicle entry points, the screw holes are prepared. After the screw insertion on the concave and convex sides of the deformity, the screws are ready to be attached to metal rods that run the length of the spine (Suk et al., 2012).

As a current trend, a high screw density is used to increase load sharing, restore, and maintain thoracic kyphosis, and correct spinal rotation (Delikaris et al., 2018). An exacting technique is needed for the accurate insertion of pedicle screws in small, deformed, and/or rotated thoracic vertebrae of the growing spine. During the surgery, intraoperative monitoring of motor evoked potentials, somatosensory potentials, and lumbar nerve root electroneuromyography are carried out to ensure the safe insertion of PSs. Furthermore, the

screw insertion accuracy is verified using fluoroscopic 2D or modern 3D intraoperative navigation techniques (Cawley et al., 2020; Santos et al., 2012). The screw fixation has excellent deformity correction and a high margin of safety in the thoracic and lumbar spine (Hicks et al., 2010; Suk et al., 2001).

After the connection of the pedicle screws and dual rods, many techniques are available to accomplish the deformity correction. These include direct vertebral derotation, *en bloc* spinal derotation, cantilever, and/or *in situ* bending maneuvers (Chang & Lenke, 2009; Mattila et al., 2013; Shah, 2007; Suk et al., 2012). If the deformity is too rigid to be corrected by a single rod, the double-rod cantilever maneuver can be performed. In this case, a second rod is added to the construct, and the two rods are connected with a cantilever arm. The cantilever arm is used to apply additional force to the spine, allowing for greater correction of the curvature (Chang, 2003).

Instrumentation material used in AIS surgery consists of stainless steel, titanium alloy, or cobalt chromium rods. The pedicle screws and dual rods work together as a single biomechanical construct in which the stress is delivered from vertebral corrective forces via screws to the rods. The success of intraoperative corrective maneuvers is therefore highly dependent on rod biomechanics. Despite extensive research, no consensus has been achieved which are the optimal biomechanical properties. Rod designs can be altered by the means of rod material, diameter, and profile (Ohrt-Nissen et al., 2018).

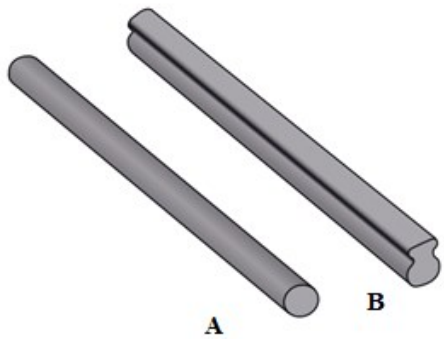

Figure 6 Traditional circular rods (A) and beam-like rods (B). The beam-like rods represent asymmetrical rods, which have larger anteroposterior diameter than the circular rods.

Posterior column osteotomies (Ponte osteotomies) with *ligamentum flavum* resection are sometimes necessary to correct significant deformities and should be considered when the instrumentation alone is unlikely to adequately correct the deformity and restore spinal balance (Ponte et al., 2018). Osteotomies are often useful when scoliotic or kyphotic curves do not bend down to 70°or less on bending or traction films (Diab et al., 2011). Several types of posterior spinal osteotomies have been described and are widely used, these include

Smith-Petersen osteotomy and Ponte osteotomy (Ponte et al., 2018; Smith-Petersen et al., 1945). The fusion is performed using local bone autograft, allograft, or bone graft extender material, which is placed over the area where the vertebrae have been modified. The graft material will eventually fuse with the vertebrae, creating a solid bony mass that stabilizes the spine.

After the surgery, the patient is closely monitored in the hospital for a few days to ensure that there are no complications. Physical therapy is typically started soon after the surgery to help the patient regain strength and mobility.

2.3.3 Posterior spinal fusion with pedicle screw instrumentation in Scheuermann´s kyphosis

Surgery for Scheuermann's kyphosis is typically reserved for patients with severe curvature causing pain or other symptoms, and who have not responded to other treatments such as physical therapy, bracing, or pain management. Like the surgical management of AIS, the surgery of SK has evolved greatly over time. The Harrington instrumentation was initially used in the management of SK but was characterized by a notable loss of correction postoperatively (Bradford et al., 1975). This unsatisfactory result was hypothesized to occur due to the lack of anterior column support. In order to minimize this complication a two-staged anterior-posterior approach was introduced and the loss of correction was significantly reduced (Bradford et al., 1980). The AP approach in the two-staged fusion and instrumentation was typically performed with a hybrid construct applying hooks, pedicle screws, and sublaminar wires.

The all-pedicle screw instrumentation with rods enhanced the surgical management of SK significantly. The AP approach is characterized by a high level of complications compared to the posterior-only approach (Lonner et al., 2007). The use of multisegmental PS instrumentation in the posterior approach allows a rigid fixation of the posterior column, and offers superior results in terms of surgical time, intraoperative blood loss, and hospitalization time when compared with the anterior approach using hybrid constructs (Koptan et al., 2009; Lee et al., 2006).

In general, the goal of surgery for Scheuermann's kyphosis is to achieve a balanced spine with adequate thoracic kyphosis, while preserving as much mobility as possible. The fusion levels are determined based on several factors, including the location and severity of the deformity, the patient's age, the flexibility of the spine, and the goals of the surgery. The general agreement is that the upper instrumented vertebra (UIV) should include the proximal end vertebra in the measured kyphosis (typically T2 or T3) to prevent proximal junctional kyphosis (PJK) (Denis et al., 2009; Lowe & Kasten, 1994). The selection of the first lordotic vertebra and sagittal stable vertebra (SSV, defined as the proximal vertebra touched by the posterior sacral vertical line) as the LIV has been reported to result in good surgical outcomes (Denis et al., 2009; Lowe & Kasten, 1994; Yanik et al., 2015).

In the surgery, the muscles and other soft tissues around the spinal column are carefully moved aside to expose the vertebrae. Apical posterior column osteotomies are performed to improve spinal flexibility before correction, up to 5° to 10° of correction can be achieved in this procedure (Ponte et al., 2018). Segmental pedicle screws are inserted into the pedicles at the length of an intended fusion. The rods are contoured to correct the deformity and restore physiological kyphosis. The rods are then attached to the screws using for example the cantilever maneuver. The term "cantilever" refers to the fact that the rods are anchored to the screws on one end, while the other end is left unsupported. The cantilever procedure is just one of several surgical options available for treating Scheuermann's kyphosis. Typically, in SK, the attachment of rods is first carried out in the proximal end. Local bone from facetectomies with bone graft extenders can be used for posterolateral spinal fusion.

2.4 Pedicle screw instrumentation related complications in the surgery of pediatric spinal deformities

The published incidence of all complications is extremely low (Hicks et al., 2010). The most common unsatisfactory outcomes in pediatric spinal deformity surgery are related to perioperative wound complications, failure to restore adequate sagittal balance, and abnormal kyphosis in the junctional areas of instrumentation. Furthermore, the placement of pedicle screws involves a risk of screw malpositioning, which can result in neurological complications. Patients with SK have a significantly higher rates of major complications, such as wound infections and reoperations than AIS patients (Lonner et al., 2015).

2.4.1 Hypokyphosis

The AIS is often characterized by preoperative hypokyphosis (i.e. kyphosis at T5-T12 <10°). The restoration of normal thoracic kyphosis and lumbar lordosis in AIS surgery is critical in optimizing clinical results and maintaining adequate sagittal balance. Hypokyphosis is associated with a scoliotic angle greater than 40° in the frontal plane and is related to the increased rotation of the apical vertebra (Matsumoto et al., 1997). It may have an adverse effect on pulmonary function and increase the risk for degenerative changes in lumbar discs (Bernstein et al., 2014; Yaszay et al., 2017). All pedicle screw instrumentation has been associated with a failure to restore adequate TK postoperatively (Lowenstein et al., 2007; Ohrt-Nissen et al., 2017; Yilmaz et al., 2012). In addition to pedicle screw and rod constructs, intraoperative corrective maneuvers has been associated with the lack of kyphosis restoration (Mladenov et al., 2011; Potter et al., 2004).

In a spine of a healthy individual, the thoracic kyphosis and lumbar lordosis are under the influence of pelvic incidence. However, in AIS, the link between the sagittal curves and the pelvic incidence is stopped at the apex of the lordosis (Clément et al., 2013). Thus, hypokyphosis in AIS can be described as a structural parameter. In the surgery of AIS, a

lumbar lordosis adapted to PI must be restored to achieve satisfactory sagittal balance. There exists conflicting evidence of a correlation between the postoperative TK correction and the magnitude of coronal Cobb angle correction (Gehrchen et al., 2016; Ohrt-Nissen et al., 2017; Quan & Gibson, 2010).

Risk factors for thoracic hypokyphosis include smaller diameter rods and preoperative hypokyphosis (Fletcher et al., 2012). Except for thicker rods, screw density of the concave side has been predicted to provide a stronger corrective force on the sagittal plane and thus lead to better restoration of TK (Luo et al., 2017). Surgical maneuvers, which increase the posterior column flexibility and length, such as posterior column osteotomies and wide facetectomies have been linked to better restoration in TK (Shah et al., 2013; Sudo et al., 2016). Other perioperative factors which affect the ability to restore TK include differential rod contour and the flexibility of the curve (Luo et al., 2017).

2.4.2 Proximal junctional kyphosis

The most encountered unsatisfactory outcome in pediatric and adolescent spinal deformity surgery is proximal junctional kyphosis (PJK). It is a postoperative radiographic phenomenon of the sagittal plane occurring at the upper instrumented vertebra after instrumented fusion surgery of scoliosis or kyphosis. In plain radiographs of pediatric patients, PJK is commonly observed as an abnormal kyphotic change in the disk space above the fusion (Cho et al., 2015). Different radiographic definitions of PJK exist. Lee et al. used a definition of abnormal kyphotic change as anything measuring ≥5° from the predicted value (Lee et al., 1999). The most frequently used definition in the literature is based on the study of Glattes et al. published in 2005. They determined PJK as a sagittal Cobb angle between the lower end plate of the upper instrumented vertebra (UIV) and the upper-end plate of the two supra-adjacent vertebrae of ≥10° and at least 10° greater than the preoperative measurement. Helgeson et al. redefined PJK as any postoperative kyphosis increase of more than 15°. In their method, PJK was measured from the caudal end plate of the UIV to the cephalad end plate of the one, instead of two, vertebra above the UIV (Helgeson et al., 2010). Depending on the cutoff value of PJK, the incidence of PJK after an AIS surgery varies between 7% and 46% (Cho et al., 2015; Helgeson et al., 2010; Kim et al., 2005; Lee et al., 1999; Lonner et al., 2017). In Scheuermann's kyphosis patients, an incidence of approximately 30% has been reported (Denis et al., 2009; Lonner et al., 2007).

Using all pedicle screw and hybrid constructs appears to increase the incidence of PJK in AIS (Cho et al., 2015; Kim et al., 2005). An increased rate of PJK has been noted in the posterior instrumentation approach when compared to the anterior technique (Rhee et al., 2002). Factors related to the incidence of PJK in PS constructs include rigidity of the instrumentation, posterior tension band disruption, posterior compression, and decreased thoracic kyphosis (Kim et al., 2005; Kim et al., 2007; Rhee et al., 2002). Thus, minimizing damage to the capsular, ligamentous, and muscular tissue, which contributes to the tension band is important. Sequential dissection of facets and posterior ligaments led to an increase

in the proximal kyphotic angle by 10% to 53% (Cammarata et al., 2014). Furthermore, soft tissue disruption, thoracoplasty, and a large preoperative TK has been hypothesized to increase the rate of PJK (Helgeson et al., 2010; Kim et al., 2005). Patients with Lenke 1 and Lenke 5 type scoliosis may have a higher risk for PJK (Lonner et al., 2017).

In SK patients, the incidence of revision surgery is also rare (Denis et al., 2009; Koller et al., 2014; Lonner et al., 2017). The implant failure and pseudarthrosis may play a greater role in the need for reoperation than the actual PJK itself. Denis et al identified fusion constructs that did not include the proximal end vertebra and disruption of *ligamentum flavum* as risk factors for PJK (Denis et al., 2009). This underlines the importance of preoperative planning and appropriate upper-end plate selection. Overcorrection of the TK may also cause junctional problems (Koller et al., 2014).

Despite the relatively high radiographic incidence of PJK, the effect of PJK on clinical and HRQoL outcomes in AIS patients remains uncertain (Cho et al., 2015). The need for revision surgery (i.e. extension of fusion proximally) is rare (Lee et al., 1999; Rhee et al., 2002). In the literature, no differences have been reported in the SRS outcome scores between patients who developed PJK and non-PJK patients (Hollenbeck et al., 2008; Kim et al., 2005; Kim et al., 2007). The effect of PJK on HRQoL in Scheuermann's kyphosis has not been studied.

2.4.3 Neurological complications

Neurological complications are among the greatest concern for parents and children undergoing instrumented spinal fusion for spinal deformities. A study based on a prospective AIS database found an overall 0.4% incidence of return to the operating room due to screw malposition between the years 2003 and 2017 (Swany et al., 2022). Reoperations caused by screw malposition decreased during the study time from 1% to 0.2%. The incidence of neural complications for posterior spinal deformity surgery is low in AIS surgery (<1%) (Bartley et al., 2017; Diab et al., 2007; Raemes et al., 2011). Bartley et al collected data from 3582 patients treated between 1995 and 2014 for AIS. There were 19 perioperative neurological complications (incidence of 0.53%) with 6 nerve root injuries, 5 spinal cord injuries, and 8 IONM alerts (Bartley et al., 2017). The overall major complication rate was 3.0%. The incidence of delayed neurological complications was 0.18%. All but two of the neurologic complications (1 nerve root and 1 spinal cord injury) had fully resolved by the time of the study. In the study of Diab et al., of 1301 consecutive instrumented spinal fusions for AIS, there were nine neural complications identified, corresponding to an incidence of 0.69% (M. Diab et al., 2007). None of them were permanent. Revision procedures and the use of corrective osteotomies may be associated with higher rates of neural complications (Raemes et al., 2011).

Together with advances in spinal deformity surgery, advances in neuromonitoring have also been made. Intraoperative neuromonitoring techniques allow the assessment of sensory and motor nerve function and spinal cord function during the surgery. Good preoperative

evaluation, delicate exposure, avoidance of excessive intraoperative stretch, and avoidance of hypotension can produce a significant reduction in neurological complications (Winter, 1997). Furthermore, intraoperative 2D and 3D imaging techniques allow for confirming the accuracy of inserted pedicle screws (Cawley et al., 2020).

2.5 Health-related quality of life

Health-related quality of life (HRQoL) is a multidimensional concept, which measures how well a person functions in their life, and what is the perceived well-being in physical, mental, emotional, and social domains of health over time (Killewo et al., 2010). In healthcare, HRQoL measurements help to determine the burden of diseases and to measure the effectiveness of the treatment on a short- and long-term basis. Various questionnaires have been developed to measure the aspects of HRQoL. Common HRQoL scales are divided into two categories: general instruments and specific instruments. General instruments (e.g., Short-Form-36 (SF-36) and EuroQol - 5 Dimension (EQ-5D)) provide a non-disease-specific outcome measure. Specific instruments are designed for a specific disease such as scoliosis. The most commonly used questionnaire in pediatric spinal deformities is SRS-22, in its various translations, which was developed by the Scoliosis Research Society. The SRS-22 is an updated version of the original SRS-24 questionnaire. The SRS questionnaires are used to measure the impact of scoliosis on a patient's self-image, function, pain, mental health, and satisfaction with management. They have been proven to have good reliability and validity (Asher et al., 2003a; Asher et al., 2003c; Parent et al., 2009).

In AIS, controversy remains regarding the strength of associations between deformity and HRQoL. It is possible that the deformity can progress while having little impact on HRQoL until reaching a threshold. Therefore, the association between HRQoL and scoliosis severity is better explained by segmented rather than linear models (Parent et al., 2010). Pain and self-image tend to be statistically lower among patients with AIS than among healthy controls (Rushton & Grevitt, 2013a; Watanabe et al., 2020). Untreated patients with adolescent or juvenile idiopathic scoliosis have similar HRQoL to brace-treated patients in adulthood (Diarbakerli et al., 2018). They have marginally higher HRQoL when compared to surgically treated patients. Evidence suggests that surgery can lead to clinically important improvement in patient self-image (Rushton & Grevitt, 2013b). Furthermore, the surgical treatment of AIS using posterior spinal fusion with pedicle screw instrumentation leads to significantly reduced back pain and improvement in the quality of life when compared to untreated individuals (Helenius et al., 2019). According to Mens et al, preoperative back pain is reported by 45% of the AIS patients preoperatively, which is reduced to 10% at the postoperative 2-year follow-up (Mens et al., 2022).

In patients with Scheuermann´s kyphosis, higher pain scores have been reported when compared with AIS patients and healthy controls (Lonner et al., 2013). There is a correlation between increased pain scores and lower overall HRQoL scores (Lonner et al., 2013). Increased pain, lower self-image, and decreased function and activity have been associated

with higher thoracic kyphosis magnitude (Lonner et al., 2013; Murray et al., 1993; Petcharaporn et al., 2007). SK patients with operative deformity have lower HRQoL outcomes than patients with operative AIS or healthy controls (Petcharaporn et al., 2007; Ragborg et al., 2020). Bracing treatment in SK patients has been associated with appearance-related anxiety, increased pain, and troubles in social interaction (Murray et al., 1993). Surgery for SK in the adolescent population results in significant improvements in HRQoL especially in self-image, which outpaces those of the AIS population (Toombs et al., 2018).

3 Aims

This thesis aimed to study the outcomes of posterior spinal fusion in pediatric spinal deformities. The outcomes were studied by analyzing the radiographic correction of the spine, rates of complications and reoperations, and the change in health-related quality of life.

1. To assess the HRQoL and radiographic outcomes of surgically treated adolescent Scheuermann's kyphosis patients and to compare their HRQoL with healthy controls after a 2-year follow-up. We hypothesized that surgical treatment with posterior spinal fusion would improve the patient's HRQoL and that it would reach the level of the healthy control group.

2. To evaluate the complication and reoperation rates, and HRQoL between AIS patients treated with posterior spinal fusion under intraoperative 3D imaging and 2D imaging. We hypothesized that advanced 3D imaging would reduce pedicle screw-related complications when compared to traditional 2D imaging (fluoroscopy).

3. To compare radiographic and HRQoL outcomes of two different designs of asymmetrical rods in AIS patients. We hypothesize that beam-like rods with dual cup PS would provide improved correction of thoracic kyphosis with similar coronal curve correction when compared with sagittal reinforced rods with tulipine PS.

4. To evaluate the association between the HRQoL and Lenke classification as well as the extent of lumbar spinal fusion in AIS patients. We hypothesized that patients in whom the spinal fusion extends to the lumbar spine have lower HRQOL when compared to patients with thoracic fusion only.

4 Materials and Methods

This study consists of four retrospective analyses using prospective data collection referred to with Roman numerals to the original articles (I-IV). The data in all studies was collected prospectively from the patient series of Turku and Helsinki University Hospitals, Finland. The study populations and study settings are described in detail below (Table 2). Prospectively collected institutional pediatric spine register was used to acquire data including clinical characteristics, radiographic parameters, health-related quality of life outcomes, and complications.

Table 2 Overview of the studies.

	Study I		**Study II**		**Study III**		**Study IV**
	Scheuermann's kyphosis	Healthy controls	2D imaging (C-arm group)	3D imaging (O-arm group)	Sagittal reinforced rods	Beam-like rods	AIS patients
Study setting	Longitudinal follow-up study and a comparative cohort study		Comparative cohort study		Comparative cohort study		Comparative cohort study
n	22	44	101	97	39	37	146
Mean age	16.7	22.0	15.5	15.5	15.8	15.4	15.1
Gender (M/F)	19/3	38/6	26/75	30/67	10/29	10/27	32/114
Mean follow-up, years	2.1	N/A	2.1	1.8	5.8	2.8	9.3

4.1 Patients

4.1.1 Study I

In study I, data of operatively treated adolescent Scheuermann kyphosis patients was collected from the institutional pediatric spine register. The HRQoL and radiographic

outcomes of patients were studied after a minimum of 2-year follow-up (mean 2.1 years, SD 0.2). The HRQoL was compared with healthy controls in a retrospective manner. The patients in study I were enrolled from Turku University Hospital between May 2009 and March 2020. There were 22 patients selected based on a diagnosis of operatively treated Scheuermann´s kyphosis of the thoracic spine. The indication for surgery was a thoracic kyphosis with a curve greater than 75°. Enrolled patients were without congenital spinal anomalies or previous spinal surgery. The mean age of the Scheuermann kyphosis patients was 16.7 years (SD 1.3 years) at the time of the surgery. Most patients (86%) were male. Of the patients, 18 (82%) underwent posterior spinal fusion at levels T2-L2, two (9%) at levels T3-L3, one (4.5%) at levels T3-L2, and one at levels T4-L2. For each patient, two healthy controls were matched for gender, and age at the final follow-up. The data of the healthy control group were derived from a previously published population-based study (Diarbakerli et al., 2017). At the time of the 2-year follow-up, the mean age of the patients was 18.8 years, and in the control group 22.0 years.

4.1.2 Study II

Study II was a retrospective comparative cohort study of patients treated operatively for AIS. The patients were enrolled from Turku University Hospital between 2009 and 2021. During this period, AIS patients were operated using two different types of intraoperative imaging methods. There were 101 (51%) patients evaluated during 2009–2016 with intraoperative 2D imaging scans (designed as a 2D group) and 97 (49%) patients evaluated during 2016–2021 with intraoperative 3D imaging scans (designed as a 3D group). The indication for surgery was a primary curve greater than a Cobb angle of 45°. The inclusion criteria were diagnosed AIS, age between 10–21 years, and posterior spinal fusion with segmental PSI. Exclusion criteria were bleeding disorder, Chiari malformation or syringomyelia in MRI, and need for anteroposterior approach or vertebral column resection. The mean age of the patients was 15.5 years in the 3D group (range 10.5 – 21.9), and 15.5 years (range 10.7 – 22.5) in the 2D group. In the 3D group, 69% of the patients were female and in the 2D group 74% were female. All patients in 2D group had 2-year FU, and in 3D group 91% of the patients reached a 2-year follow-up. The mean FU time was 2.0 years (range from 0.5 to 3.2 years).

4.1.3 Study III

Study III was a retrospective comparative cohort study of patients treated operatively for AIS. The patients were enrolled from Turku University Hospital between 2015 and 2020. Patients with curves classified as Lenke 5 or 6 (thoracolumbar/lumbar main curve) primarily undergo selective fusion of the thoracolumbar spine and were therefore excluded from the study. During the study period, two different types of pedicle screw instrumentation were used in the operative treatment of AIS. The patients treated between 2015 and 2017 were

operated with sagittal reinforced rods and tulipine pedicle screw instrumentation (Solera 5.5/6.0 mm, Medtronic, Minneapolis, Minnesota, USA). The patients treated between 2018 and 2020 were operated with beam-like rods and dual-cup pedicle screw instrumentation (Mesa 2, Stryker, Portage, Michigan, USA). There were 39 AIS patients treated with sagittal reinforced rods (designated as SRR group), and 37 patients treated with beam-like rods (designated as BLR group). The mean age at surgery was 15.8 years (SD 2.1) and 15.4 years (SD 1.9) in SRR and BLR groups, respectively (p=0.193). In the SRR group 34% and in the BLR group 37% of the patients were male. The 2-year follow-up data were available in 39/39 (100%) of the patients in the sagittal reinforced rod group, and in 35/37 (95%) of the patients in the beam-like rod group.

4.1.4 Study IV

Study IV was a prospective comparative cohort study of adolescent patients who underwent operative treatment for AIS. All consecutive 162 AIS patients operated at Helsinki and Turku University Hospitals between 2007 and 2019 were evaluated. Patients lacking preoperative or two-year HRQoL follow-up data were excluded from the study. There were 146 patients of which analyses were performed preoperatively, at six months of follow-up, and at two years of follow-up. Patients were classified into the study groups based on the Lenke classification. There were 56 patients with Lenke 1 (38%), 38 patients with Lenke 2 (26%), 10 patients with Lenke 3 (6.8%), 7 patients with Lenke 4 (4.8%), 22 patients with Lenke 5 (15%), and 13 patients with Lenke 6 (8.9%) scoliosis. Mean follow-up time was 9.3 years (range from 2.3 to 16 years). Of them 53 patients reached a 10-year follow-up.

4.2 Surgical Techniques

Patients in all studies were operated with multisegmental posterior spinal fusion using pedicle screw insertion along with *en bloc* direct vertebral derotation. In study IV, eleven patients with Lenke 5 scoliosis were operated using an anterior approach (thoracoabdominal) and anterior instrumented fusion (CD Legacy anterior, Medtronic) between T10 and L3 (from end vertebra to end vertebra) with anterior structural cages below L1. Intraoperative spinal cord monitoring (motor evoked potentials, somatosensory potentials, lumbar nerve root electroneuromyography) was used in all patients.

In patients with SK, the correction of kyphosis was performed using a double rod cantilever maneuver (proximal to distal) and with additional apical compression closing the apical posterior column osteotomies. Local bone from facetectomies with bone graft extenders was used for posterolateral spinal fusion. Apical posterior column osteotomies were performed in all patients to facilitate deformity correction. The number of posterior column osteotomies was based on the flexibility of kyphosis intraoperatively. Segmental

pedicle screw instrumentation was inserted from the sagittal stable vertebra using the posterior sacral vertical line (typically L2) to the upper thoracic spine (typically T2 or T3).

In AIS patients, the selection of fusion levels was based on the Lenke classification and the last substantially touched vertebra (Beauchamp et al., 2020). Apical posterior column osteotomies (i.e., Ponte procedure) were performed when necessary. Screw placement was verified using intraoperative cone-beam computed tomography (CT) scans (O-arm, Medtronic). The segmental PSI was performed bilaterally. The pedicle screw instrumentations used in the patients were either sagittal reinforced rods (6.0 CoCr Apex Rod, Solera 5.5/6.0 Instrumentation, Medtronic) with tulipine pedicle screws or beam-like rods (Mesa 2, Stryker) with dual cup pedicle screws. Screw diameters varied from 4.5 mm to 6.5 mm. The screw placement was standardized including three pairs of polyaxial screws on top of the construct, uniplanar screws in the midthoracic spine, a single polyaxial screw in the concave apex, and polyaxial screws in the lumbar spine. The placement of the pedicle screws was verified using intraoperative 2D or 3D imaging. Patients with Lenke 5 scoliosis were operated using anterior approach (T11-L3, n=10) or using PSI (n=136).

4.3 Outcome Parameters

The patients followed a standardized protocol, including preoperative and immediate postoperative assessment, and follow-up visits at the outpatient clinic at 6-month and 2-years.

4.3.1 Radiographic outcomes

Standing antero–posterior (AP) and lateral spinal radiographs were collected preoperatively and at the follow-ups. Preoperative bending radiographs were used to assess structural curves. Cobb angles and central sacral vertical line (CSVL) were measured from AP radiographs. The following parameters were measured from lateral radiographs: thoracic kyphosis (T2–T12 and T5-T12), major thoracic (MT) kyphosis, lumbar lordosis (T12-S1), sagittal vertical axis (SVA), pelvic incidence (PI), pelvic tilt (PT), and sacral slope (SS) angles. The proximal junctional kyphosis (PJK) was defined by two criteria: a proximal junctional sagittal Cobb angle ≥10° and at least 10° greater than the preoperative measurement (Helgeson et al., 2010). Thoracic kyphosis less than 10° was considered hypokyphosis (Lenke et al., 2001). The deformities were classified according to the Lenke classification (Lenke et al., 2001). Sagittal balance was evaluated using the distance between C7 plumbline and posterosuperior corner of the sacrum (Spinal deformity measurement manual, Medtronic). Minor curves were classified as structural or nonstructural using the supine bending radiographs. In study II, pedicle screw placement in the 2D group was intraoperatively evaluated using posteroanterior and lateral fluoroscopic imaging after all screws were placed. Non-harmonious screws or screws violating bony landmarks were

identified. In the 3D group, the O-arm spins of every screw were obtained at the end of free hand screw placement.

4.3.2 Health-related quality of life outcomes

In all studies, the HRQoL of patients was assessed using the disease-specific Scoliosis Research Society-24 (SRS-24) questionnaire (Haher et al., 1999). The questionnaire has 24 questions divided into seven domains: pain, general self-image, general function, and general activity level. Each item is scored on a 5-point Likert-type scale from one to five and the maximum score is 120. A higher score indicates better patient outcome. Questions number 16–24 concern postoperative self-image, postoperative function, and patient satisfaction with the treatment, and are filled out only postoperatively.

In study I, the control group filled out the SRS-22r questionnaire, which is an improved version of the original SRS-24 (Asher et al., 2003b; Haher et al., 1999). The first 15 questions of the SRS-24 are the same as or close to questions in the SRS-22r. Questions number 1–15 of SRS-24 corresponds with questions 1, 2, 4, 5, 6, 8, 9, 11, 12, 14, 15, and 17–20 of the SRS-22r. These questions were used as a basis for four domains. They were formed as follows: pain (SRS-24: 1, 2, 3, 6, 8, and 11; SRS-22r: 1, 2, 4, 8, 11, and 14), general self-image (SRS-24: 5, 14, and 15; SRS-22r: 6, 19, and 20), general function (SRS-24: 7, 12, and 13; SRS-22r: 9, 15, and 18), and general activity (SRS-24: 4, 9, and 10; SRS-22r: 5, 12, and 17). In addition, the scores of the eight questions that are the same in both SRS-24 and SRS-22r questionnaires were compared between patients and controls (questions one through eight in the SRS-24 and 1, 2, 4, 5, 6, 8, 9, and 11 in the SRS-22r).

4.4 Statistical Analysis

The normal distribution assumption of the data was verified visually with QQ-plot and with the Shapiro–Wilk test. Descriptive statistics were presented in absolute numbers and percentages or in mean values with standard deviations (SDs) for variables following a normal distribution. For variables that did not follow a normal distribution, medians with first (Q1), and third (Q3) quartiles were presented.

In study I, comparison of radiographic outcome data was performed with paired *t*-test. The comparison of preoperative or 6-month follow-up domain scores with 2-year follow-up scores was carried out with paired t-test. Two-sample t-test assuming equal variances in the HRQoL domain scores was applied to compare patients with healthy controls. In study II, statistical comparisons between the groups were performed with the chi-squared test for categorical parameters and with an independent-samples t-test for continuous variables. In study III, associations among categorical variables were investigated by the χ^2-test or Fisher exact test. The comparisons between the study groups were performed using a two-sample t-test, one-way analysis of variance, or the Wilcoxon rank-sum test. The correlation between

the main thoracic curve correction and TK restoration was calculated with the Kendall correlation coefficient. In study IV, the association between repeated HRQoL measurements in each patient and quality of life scores were analyzed using repeated measures mixed model. Timepoint and Lenke-group were considered as fixed factors and patients as random factors. SRS-24 data are presented with means and 95% confidence intervals.

P-values < 0.05 were considered statistically significant. All analyses were conducted in JMP® for Macintosh, Version 16.1 (SAS Institute Inc., Cary, NC, USA, 1989–2021) in studies I, II, and in studies III and IV in R (R 4.1.1, R Core Team, 2020).

4.5 Ethical Aspects

Institutional approvals were permitted by Turku University Hospital and Helsinki University Hospital. The studies included in this thesis received approvals from the ethical committees of Turku University Hospital and Helsinki University Hospital (ETMK 96/1801/2020 and ETMK 38/1800/2015). A written informed consent was acquired from the patients and normative population and, when needed, from their guardians.

5 Results

5.1 Health-related quality of life in adolescents with Scheuermann's kyphosis treated with posterior spinal fusion (Study I)

The baseline data of the patients are presented in Table 3. The mean BMI was 25.9 kg/m^2 (range 16-40) preoperatively. The median number of posterior column osteotomies was 4 (range 2-7). The average duration of surgery was 3.6 hours (range 2.75 – 7 hours) with an average blood loss of 631 mL (range 300-1450 mL).

Table 3 Clinical characteristics of the study groups in study I.

	Scheuermann's kyphosis patients (n=22)	**Healthy controls (n=44)**
Age at surgery, years, (SD)	16.7 (1.3)	N/A
Age at 2-year FU, years, (SD)	18.8 (1.1)	22.0 (7.6)
Gender (M/F)	19/22	38/44
BMI (kg/m^2), (SD)	25.9 (7.7)	
Levels fused		
T2-L2	82% (18/22)	
T3-L3	9% (2/22)	
T3-L2	4.5%(1/22)	
T4-L2	4.5%(1/22)	

Radiographic outcomes are presented in Table 4. Thoracic kyphosis and lumbar lordosis were reduced in operative treatment, and the results persisted during the follow-up. While the kyphosis and lordosis were corrected, the sagittal balance of the patients was successfully preserved. Preoperative thoracic kyphosis (T5-T12) was 79° (SD 5°) and at 2-year follow-up 42° (SD 9°) ($p<0.001$). The mean major thoracic kyphosis improved from 79° (SD 8°) to 55° (SD 10°) ($p < 0.001$). The average lumbar lordosis was reduced from 71° (SD 12°) to 52° (SD 10°) ($p<0.001$).

During the follow-up pelvic tilt changed from 7° (SD 7°) to 9° (SD 5°) ($p=0.353$) and sacral slope from 38° (SD 14°) to 30° (SD 9°) ($p=0.073$). The central sacral vertical line

was 13 mm preoperatively and 10 mm at the 2-year follow-up (p=0.368). The sagittal balance averaged 28 mm preoperatively, and 29 mm at the final follow-up (p=0.925).

Table 4 Radiographic outcomes of the SK patients in study I. The results are presented as means with standard deviation.

	Preoperative	**6-month FU**	**2-year FU**	**p-value**
Maximal kyphosis	79° (7°)	52° (9°)	55° (10°)	<0.001
Kyphosis T2-T12	76° (7°)	47° (7°)	52° (9°)	<0.001
Kyphosis T5-T12	79° (5°)	42° (8°)	42° (9°)	<0.001
Lordosis T12-S1	71° (12°)	52° (8°)	52° (10°)	<0.001
Sagittal vertical axis	28 mm (20)	23 mm (15)	29 mm (20)	0.925
Pelvic tilt	7° (7°)	9° (7°)	9° (5°)	0.353
Sacral slope	38° (14°)	33° (9°)	30° (9°)	0.073
Central sacral vertical line	13 mm (11)	10 mm (7)	10 mm (10)	0.368
Coronal Cobb angle	12° (8°)	8° (8°)	8° (6°)	0.122
Proximal junctional angle	N/A	6° (5°)	7° (7°)	0.692

During the initial surgery, there was a change in motor evoked potential (MEP) in one patient. The patient had one pedicle screw removed intraoperatively and had no neurologic deficit during the follow-up. One patient had a deep surgical site infection and underwent revision surgery. The proximal junctional kyphosis was observed in 4 patients (18%). All patients with PJK were asymptomatic and were treated conservatively.

The health-related quality of life was assessed using the SRS-24 questionnaire preoperatively, and at 6-month and 2-year follow-ups. The HRQoL scores of the SK patients are presented in Table 5. Preoperatively, 21 patients (95%) completed the questionnaire. Twenty (91%) patients completed the same questionnaire at 2 years postoperatively. The HRQoL of patients who had PJK did not differ significantly from other patients in any of the SRS domains at 2 years postoperatively. The radiographic correction of the deformity did not show any statistical correlations between the SRS questionnaire domains.

Table 5 The SRS-24 domain scores of the SK patients in study I. The results are presented as means with standard deviation.

	Preoperative (n=21)	6-month FU (n=19)	2-year FU (n=20)	p-value
Total	4.08 (0.54)	3.93 (0.45)	4.21 (0.42)	0.202
Pain	3.99 (0.66)	4.41 (0.50)	4.51 (0.45)	0.002
Self-image	3.52 (0.92)	3.83 (0.75)	4.06 (0.70)	0.002
Function	3.79 (0.98)	4.04 (0.73)	4.22 (0.34)	0.076
Activity	4.33 (1.07)	3.74 (1.12)	4.63 (0.77)	0.421
Postop self-image	N/A	3.52 (0.51)	3.83 (0.70)	0.167
Postop function	N/A	2.28 (1.02)	2.78 (1.00)	0.150
Satisfaction	N/A	4.39 (0.50)	4.44 (0.64)	0.894

A comparison of HRQoL data of SRS outcomes between surgically treated patients and age- and sex-matched controls is presented in Table 6. The SRS scores for self-image and function remained significantly lower in the operated patients at their 2-year follow-up ($p=0.023$ for self-image and $p<0.001$ for function). The pain and activity domain scores were similar in patients as compared with the healthy controls.

Table 6 A comparison of HRQoL domain scores between patients and controls in study I. The results are presented as means with standard deviation.

	Patient 2-years FU (n=20)	Healthy controls (n=44)	p-value
Total*	4.45 (0.44)	4.56 (0.43)	0.355
Pain*	4.60 (0.47)	4.65 (0.50)	0.730
Self-image	4.06 (0.70)	4.46 (0.57)	0.023
Function	4.22 (0.34)	4.82 (0.40)	<0.001
Activity	4.63 (0.77)	4.67 (0.42)	0.809
Total of eight same questions	4.55 (0.47)	4.55 (0.49)	0.992

* The questions regarding postoperative state excluded.

5.2 Comparison of pedicle screw related complications and re-operations between intraoperative 2D and 3D imaging (Study II)

A total of 198 consecutive adolescents treated operatively for AIS were identified from patient records of Turku University hospital. The baseline data are presented in Table 7. There were 1931 pedicle screws used in the operative treatment in the 3D group and 2048

screws in the 2D group. The age, gender distribution, degree of the major thoracic curve correction, and HRQoL data were similar between the groups. The mean Cobb angle of the main curve in the study population was 52° (SD 8°) at the time of the surgical procedure, with a remaining curve of 13° (SD 5°) at the final follow-up and did not differ between the study groups.

Table 7 Clinical characteristics of the groups in study II.

	3D group (n=97)	**2D group (n=101)**	**p-value**
Age at surgery, years, range	15.5 (10.5-21.9)	15.5 (10.7-22.5)	0.867
Gender (M/F)	30/67	26/75	0.418
Mean follow-up, years, range	1.8 (0.5-2.6)	2.1 (0.54-3.2)	<0.001
Major preoperative thoracic curve, degrees	52° (45-83)	53° (45-84)	0.138*
Major postoperative thoracic curve, degrees	13° (2-28)	12° (2-24)	
SRS-24 total score, mean, range			
Preoperative	3.7 (2.4–4.6)	3.8 (2.5–4.4)	0.462
6-months follow-up	3.9 (2.4-4.6)	3.8 (2.7–4.7)	0.393
2-year follow-up	4.1 (2.5-4.7)	4.0 (2.9–4.6)	0.271

*Comparison of the MT curve correction between the study groups.

In the index operation, 44 patients (45%) in the 3D group and 13 patients (13%) in the 2D group had at least one pedicle screw repositioned (p<0.001). The number of replaced screws was higher in the 3D group (70 screws, 3.6% of all screws, average 0.73 per patient, range 0–4) as compared with the 2D group (13 screws, 0.63%, average 0.13 per patient, range 0–2) (p<0.001). In the 3D group, 43 of the replaced screws breached the medial wall (61%, mean breach 3.2 mm, range 2–6.5 mm), 17 breached the lateral wall of the pedicle (24%, mean breach 3.6 mm, range 2–6), and 10 the anterior cortex (15%, mean breach 2.7 mm, range 1.1–5 mm) of the vertebrae (Figure 7). Four patients in the 3D group and one in the 2D group had a screw replaced due to a sagittal breach.

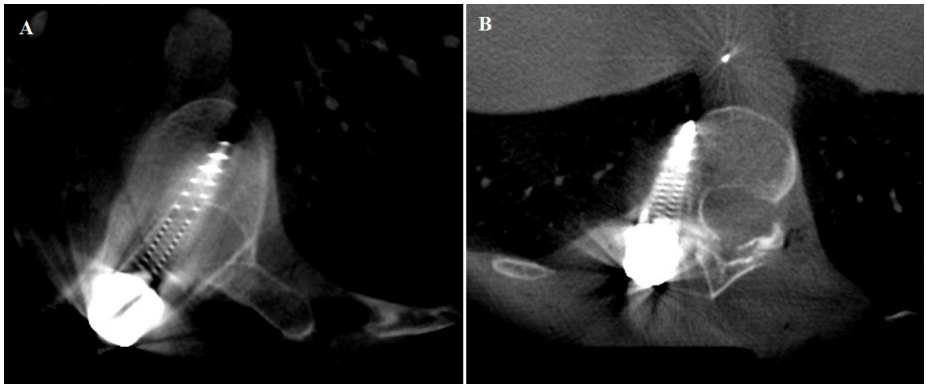

Figure 7 Pedicle screws breaching medial wall (A) and lateral wall (B).

The complications and reoperations are listed in Table 8. A decrease of the MEP of 50% or more intraoperatively was observed in nine patients in the 2D groups as compared with one patient in the 3D group (p=0.011). There were six new neurologic deficits in the 2D group as compared with none in the 3D group (p=0.015). An intraoperative cerebrospinal fluid leak occurred in one patient in the 2D group, and in two patients in the 3D group (p=0.534). A delayed cerebrospinal fluid leak occurred in two patients in the 2D group as compared with none in the 3D group (p=0.100). Three patients in the 2D group had superficial surgical site infection as compared with none in the 3D group (p=0.043). There were no deep surgical site infections in the study population.

Table 8 Complications and reoperations in study II.

	3D group	**2D group**	**P-value**
Intraoperative monitoring change	1	9	0.011
Neurologic complication	0	6	0.015
Motor deficit	0	4	0.048
Cerebrospinal fluid leak	2	3	0.683
Intraoperative	2	1	0.534
Delayed	0	2	0.100
Surgical site infection			
Superficial	0	3	0.043
Deep	0	0	N/A
Reoperations	0	5	0.009

There were 5 reoperations in the 2D group and none in the 3D group (p=0.028). New motor deficits were observed in 4 patients in the 2D group ranging from muscle weakness to paresis. Three of these patients were reoperated within 48 hours after the initial surgery. Two patients in the 2D group developed postural headaches due to delayed dural lesions

and required reoperation approximately three months after the initial surgery. None of the patients who underwent reoperation had wound-related complications.

5.3 Comparison thoracic kyphosis restoration between sagittal reinforced rods and beam-like rods (Study III)

The distributions of age, gender, and Lenke classification were similar between the groups (Table 9). The overall length of follow-up was significantly longer in the reinforced rod group (5.3 years; SD, 0.8) than in the beam-like rod group (2.8 years; SD, 1.3) ($p < 0.001$). The mean number of fused levels was 11.3 in the SRR group, and 11.6 in the BLR group (p=0.200). The mean number of osteotomies was 3.1 in the SRR group, and 2.4 in the BLR group (p=0.109). The mean total score of SRS-24 was preoperatively 4.0 in the SRR group and 4.0 in the BLR group (p=0.796). At the 2-year FU, the mean scores were 3.9 and 4.3 in SRR and BLR groups, respectively (p=0.003).

Table 9 Clinical characteristics of the groups in study III.

	Sagittal Reinforced Rod Group (n=39)	**Beam-Like Rod Group (n=37)**	**p-value***
Age at surgery, years, SD	15.8 (2.1)	15.4 (1.9)	0.193
Gender (M/F)	10/29	10/27	0.890
Mean follow-up, years, SD	5.8 (0.8)	2.8 (1.2)	<0.001
Mean number of fused levels	11.3 (1.8)	11.6 (1.4)	0.200
Mean posterior column osteotomies	3.1 (0.2)	2.4 (0.3)	0.109
Lenke classification, n (%)			
1	16 (42.1%)	13 (37.1%)	0.340†
2	14 (36.8%)	16 (45.7%)	
3	3 (7.9%)	5 (14.3%)	
4	5 (13.2%)	1 (2.9%)	
SRS-24 total score, SD			
Preoperative	4.0 (0.7)	4.0 (0.5)	0.796
2-year follow-up	3.9 (0.6)	4.3 (0.3)	0.003

* Values calculated using two-sample t-test unless stated otherwise

† Value calculated using chi-square test

The radiographic outcomes are presented in Table 10. Preoperatively, the MT curve was 54° in the SRR group, and 51° in the BLR group (p=0.057). The MT curve in preoperative bending radiographs was similar between the groups. The results in the MT curve were

similar between the groups in 6-months (11° in the SRR group and 13° in the BLR group, p=0.160) and 2-year (13° in the SRR group and 13° in the BLR group, p=0.717) follow-ups. The preoperative TK was 21° in the SRR group and 23° in the BLR group (p=0.302). The mean TK was 22° and 20° (p=0.165) at 6-month and 24° and 22° (p=0.517) at 2-year follow-ups in the SRR group and BLR group, respectively. The mean lordosis was preoperatively 51° in the SRR group and 57° in the BLR group (p=0.032). At the 6-month follow-up, the mean lordosis was 48° in the SRR group and 49° in the BLR group (p=0.433). At the 2-year follow up the mean lordosis was 51° in the SRR group and 50° in the BLR group (p=0.435).

Table 10 The radiographic outcomes of the patients in study III. All values are presented as mean with standard deviation.

	Sagittal Reinforced Rod Group (n=39)	**Beam-Like Rod Group (n=37)**	**p-value**
Main thoracic curve			
Preoperative	54° (10°)	51 (5°)	0.057
Preoperative bending	36 (13°)	34 (8°)	0.237
6-month FU	11 (6°)	13 (6°)	0.160
2-year FU	13 (6°)	13 (6°)	0.717
Thoracic kyphosis			
Preoperative	21 (15°)	23 (14°)	0.302
6-month FU	22 (7°)	20 (8°)	0.165
2-year FU	24 (11°)	22 (8°)	0.517
Lordosis			
Preoperative	51 (12°)	57 (16°)	0.032
6-month FU	48 (13°)	49 (12°)	0.433
2-year FU	51 (11°)	50 (12°)	0.435

The mean MT curve correction was 75% in the SRR group and 73% in the BLR group (p=0.467). The thoracic kyphosis had a mean increase of 3° in the SRR group and a mean decrease of 1° in the BLR group (p=0.855). The kyphosis correction ranged from -65% to +400% in the SRR group (mean correction 42%) and from -100% to +300% in the BLR group (mean correction 32%) (p=0.744). A slight negative correlation was found between the MT curve correction and change in the thoracic kyphosis in both study groups (R = −0.19, P = 0.094 in the SRR group; R = −0.16, P = 0.180 in the BLR group).

In the SRR group seven patients and in the BLR group three patients had preoperative hypokyphosis (T5–T12 kyphosis <10°) (p=0.205). In the SRR group, two patients remained hypokyphotic at the 2-year follow-up compared to one patient in the BLR group (p=0.587). There were no neurological complications, deep surgical site infections, or mechanical

complications in either study group. In the SRR group, one patient underwent reoperation with an extension of the instrumentation for distal junctional kyphosis 1-year after the initial surgery without any further sequelae in the follow-up.

5.4 Association between Lenke classification, the extent of lumbar spinal fusion, and HRQoL after instrumented spinal fusion in adolescent idiopathic scoliosis (Study IV)

The clinical characteristics of the study groups are presented in Table 11. The distributions of age and gender were similar between the groups. The largest mean preoperative major curve was observed in patients in Lenke 3 (mean 63°, 95%CI 54.5–71.3) and Lenke 4 (mean 62°, 95%CI 57.2–67.2) groups. Preoperative thoracic kyphosis and lumbar lordosis were similar between the study groups.

Table 11 Clinical characteristics of the study groups in study IV.

	Lenke 1	Lenke 2	Lenke 3	Lenke 4	Lenke 5	Lenke 6
n, (%)	56 (38)	38 (26)	10 (6.8)	7 (4.8)	22 (15)	13 (8.9)
Age at surgery, years (SD)	15.4 (2.1)	15.5 (2.6)	15.3 (2.4)	15.0 (0.8)	15.9 (1.5)	15.7 (2.4)
Gender (M/F)	11/45	8/30	3/7	4/3	4/18	2/11
Operative time, hours, (SD)	3.1 (0.9)	2.9 (0.6)	3.6 (1.1)	3.7 (0.9)	3.1 (1.1)	3.5 (0.7)
Intraoperative blood loss, mL, (range)	430 (250–650)	456 (324–600)	400 (340–980)	515 (562–720)	393 (210–550)	600 (380–705)

The radiographic outcomes of the study groups are presented in Table 12. At the 2-year follow-up, the degree of mean major curve was similar between the groups. The mean TK and LL were lower in Lenke 1 and Lenke 2 groups when compared to other study groups (p=0.003 and p=0.020 for TK and LL, respectively). The mean thoracic kyphosis was largest in the Lenke 4 group (mean TK 25°, SD 9.2) and lowest in the Lenke 2 group (mean TK 16°, SD 6.2). The mean lumbar lordosis was largest in the Lenke 5 group (mean LL 57°, SD 8.7) and lowest in the Lenke 2 group (mean LL 45°, SD 14).

Table 12 Radiographic outcomes of the study groups.

	Lenke 1	Lenke 2	Lenke 3	Lenke 4	Lenke 5	Lenke 6	p-value*
Preoperative							
MC, (SD)	51 (5.8)	53 (8.2)	63 (12)	62 (5.4)	48 (5.1)	55 (6.5)	
TK, (SD)	20 (13)	18 (9.5)	27 (14)	21 (2.1)	29 (14)	26 (11)	
LL, (SD)	50 (14)	53 (12)	59 (14)	50 (8.7)	53 (10)	56 (9.4)	
6-month FU							
MC, (SD)	13 (5.4)	12 (6.2)	16 (5.2)	17 (6.8)	12 (7.9)	12 (7.3)	0.338
TK, (SD)	19 (7.6)	16 (6.4)	28 (10.1)	19 (2.0)	24 (6.5)	21 (7.8)	0.001
LL, (SD)	47 (11)	46 (12)	48 (11)	51 (5.1)	55 (6.9)	52 (7.6)	0.081
2-year FU							
MC, (SD)	13 (6.1)	13 (6.6)	16 (8.2)	16 (6.1)	14 (7.2)	14 (6.0)	0.734
TK, (SD)	19 (8.2)	16 (6.2)	24 (6.8)	25 (9.2)	24 (5.0)	24 (7.1)	0.003
LL, (SD)	47 (11)	45 (14)	54 (16)	50 (7.4)	57 (8.7)	54 (8.9)	0.020

* Comparison to preoperative situation.

The results of HRQoL are presented in Table 13. Preoperatively, the scores of SRS-24 were similar between the groups. During the 2-year FU, the total score remained lowest in the Lenke 5 and Lenke 6 groups. At the 6-month FU, total and pain domain scores were lower in the Lenke 5 groups when compared with Lenke 1 group. These differences were not observed in the 2-year FU. Self-image domain was significantly lower in Lenke 5 group when compared to Lenke 2 group at the two-year follow-up (mean 3.61, 95%CI 3.29–3.92 vs. mean 4.33, 95%CI 4.07–4.58). Postoperative satisfaction domain was lower in Lenke 5 when compared to Lenke 1 and Lenke 2 groups at six months (Lenke 5 mean 3.68, 95%CI 3.41–3.95 vs. Lenke 1 mean 4.34, 95%CI 4.17–4.52; Lenke 2 mean 4.26, 95%CI 4.06–4.47) and at two years follow-up (Lenke 5 mean 3.76, 95%CI 3.49–4.03 vs. Lenke 1 mean 4.34, 95%CI 4.17–4.51; Lenke 2 mean 4.38, 95%CI 4.16–4.60).

Table 13 Results of SRS-24 questionnaire domains in the study groups.

	Lenke 1 (n= 56)	**Lenke 2 (n=33)**	**Lenke 3 (n=10)**	**Lenke 4 (n=7)**	**Lenke 5 (n=22)**	**Lenke 6 (n=13)**
Preoperative						
Total	3.97 ± 0.07	4.11 ± 0.08	4.13 ± 0.16	4.23 ± 0.19	3.90 ± 0.11	4.05 ± 0.14
Pain	3.44 ± 0.09	3.54 ± 0.11	3.72 ± 0.21	3.64 ± 0.27	3.27 ± 0.14	3.48 ± 0.19
Function	4.00 ± 0.07	4.05 ± 0.08	4.07 ± 0.16	4.33 ± 0.12	4.08 ± 0.11	3.92 ± 0.14
Self-image	3.63 ± 0.11	3.74 ± 0.13	3.73 ± 0.25	3.83 ± 0.33	3.52 ± 0.17	3.87 ± 0.22
Activity	4.53 ± 0.09	4.66 ± 0.11	4.63 ± 0.22	4.86 ± 0.26	4.33 ± 0.15	4.64 ± 0.19
6-month FU						
Total	3.90 ± 0.06	3.86 ± 0.07	3.88 ± 0.13	3.83 ± 0.16	3.57 ± 0.09	3.80 ± 0.11
Pain	4.31 ± 0.09	4.19 ± 0.11	4.44 ± 0.20	4.41 ± 0.24	3.87 ± 0.13	4.35 ± 0.18
Function	3.98 ± 0.07	3.97 ± 0.08	3.97 ± 0.16	3.67 ± 0.19	3.86 ± 0.11	3.75 ± 0.15
Self-image	4.03 ± 0.10	4.15 ± 0.12	3.83 ± 0.24	3.95 ± 0.28	3.61 ± 0.16	3.89 ± 0.21
Activity	4.02 ± 0.12	4.08 ± 0.15	3.97 ± 0.29	4.00 ± 0.34	3.91 ± 0.19	3.97 ± 0.26
Post-op. self-image	3.30 ± 0.07	3.28 ± 0.08	3.20 ± 0.16	3.33 ± 0.19	3.14 ± 0.11	3.33 ± 0.15
Post-op. function	2.25 ± 0.13	1.97 ± 0.16	2.20 ± 0.32	2.14 ± 0.38	2.00 ± 0.21	1.79 ± 0.29
Post-op. satisfaction	4.34 ± 0.09	4.26 ± 0.11	4.20 ± 0.21	3.95 ± 0.25	3.68 ± 0.14	4.03 ± 0.19
2-year FU						
Total	4.08 ± 0.05	4.13 ± 0.06	4.00 ± 0.12	4.11 ± 0.14	3.81 ± 0.08	3.90 ± 0.11
Pain	4.36 ± 0.08	4.32 ± 0.10	4.37 ± 0.18	4.61 ± 0.22	4.08 ± 0.12	4.22 ± 0.16
Function	4.17 ± 0.06	4.21 ± 0.08	4.23 ± 0.14	4.24 ± 0.17	4.14 ± 0.10	4.18 ± 0.12
Self-image	4.05 ± 0.10	4.35 ± 0.13	3.67 ± 0.24	3.90 ± 0.28	3.61 ± 0.16	3.77 ± 0.21
Activity	4.67 ± 0.08	4.79 ± 0.11	4.47 ± 0.19	4.90 ± 0.23	4.59 ± 0.13	4.74 ± 0.17
Post-op. self-image	3.36 ± 0.07	3.34 ± 0.09	3.33 ± 0.17	3.10 ± 0.21	3.21 ± 0.12	3.08 ± 0.15
Post-op. function	2.84 ± 0.10	2.88 ± 0.13	2.80 ± 0.24	2.86 ± 0.29	2.50 ± 0.16	2.38 ± 0.21
Post-op. satisfaction	4.35 ± 0.08	4.37 ± 0.11	4.20 ± 0.20	4.10 ± 0.24	3.76 ± 0.13	3.97 ± 0.18

The patients with lowest instrumented vertebra in L3 or lower had a trend of lower SRS-24 scores. However, these differences remained statistically insignificant. There was no association between the type of thoracic kyphosis (hypokyphosis <10°, normal 10-40°,

hyperkyphosis >40°) with the SRS-24 total score or the subdomains during the 2-year FU. The amount of lumbar residual curve was not associated with SRS-24 total score or self-image domain.

Fifty-three (38%) patients reached a 10-year follow-up. The SRS-24 total score averaged 4.06 (SD 0.51) preoperatively, 3.93 (SD 0.39) at six months, 4.10 (SD 0.34) at 2-year, and 3.90 (0.47) at 10-year follow-up (p=0.040 for preoperative vs. 10-year). The highest mean total score of SRS-24 after 10-year follow-up was observed in the Lenke 1 group (mean score 4.06, 95% CI 3.79 - 4.33) and lowest in the Lenke 6 group (mean 2.92, 95% CI 2.22 - 3.61) (Table 14). At the 10-year follow-up, the SRS-24 domains for pain, satisfaction and total scores were higher in patients with LIV at L2 or higher levels as compared to patients with LIV at L3 or lower levels (p<0.029 for all comparisons).

Table 14 The HRQoL outcomes in the study groups at 10-year follow-up (n=53).

Study group	n	SRS-24 total score (mean, 95% CI)
Lenke 1	27	4.06 (3.79 - 4.33)
Lenke 2	10	3.97 (3.53 – 4.41)
Lenke 3	9	3.81 (3.35 – 4.28)
Lenke 4	1	3.94 (N/A)
Lenke 5	2	3.31 (2.33 – 4.30)
Lenke 6	4	2.92 (2.22 – 3.61)

There were four patients requiring pedicle screw repositioning during the initial surgery. Two of these patients had Lenke 3 scoliosis, one patient had Lenke 1, and one patient Lenke 6 scoliosis. No further complications occurred in these patients. Postoperatively, one patient with Lenke 1 scoliosis had weakness of lower extremity function. The patient was diagnosed with T11 screw malposition. The screw was removed in revision procedure without further complications. One patient with Lenke 2 scoliosis had a loss of MEP signal during the initial surgery. The primary surgery was aborted, patient recovered, and surgery was finished one week later without further sequel. One patient with Lenke 1 scoliosis developed a deep surgical site infection 4 years after the initial surgery requiring removal of the instrumentation.

6 Discussion

In this thesis, we assessed the influence of operative treatment on the HRQoL of the patients with Scheuermann's kyphosis. Furthermore, we produced novel information on what is the quality of life of the SK patients after 2-year FU when compared to healthy individuals. We evaluated the complication and reoperation rates between two different intraoperative imaging methods. Our data had a relatively large patient population and a high number of inserted pedicle screws. We provided a better understanding of the thoracic kyphosis restoration between sagittal reinforced rods and beam-like rods. Finally, we produced novel information on the effects of Lenke classification and the length of instrumentation on postoperative HRQoL in AIS patients.

The clinical goals of treatment for adolescent idiopathic scoliosis are to correct the present deformity, to prevent the progression of the deformity, and to restore trunk symmetry and balance. Segmental pedicle screw instrumentation in AIS was introduced by Suk et al. and since then has been under continuous development (Suk et al., 1995). When compared to prior segmental correction methods, posterior fusion surgery using PSI has several advantages compared to traditional instrumentation, including enhanced 3D correction and reduced number of levels that need to be fused (Helenius et al., 2003; Liljenqvist et al., 1997; Suk et al., 1995).

Patients with operative SK are more symptomatic in all SRS-22 and SRS-24 domains than healthy subjects (Lonner et al., 2013; Petcharaporn et al., 2007). We hypothesized that PSF using PSI would result in improved HRQoL and would reach the level of healthy controls. In study I, improved HRQoL was seen in all SRS-24 domains of SK patients. When we compared the SRS outcomes of Scheuermann´s kyphosis patients with age and sex-matched healthy controls, we noticed that the HRQoL of patients in pain and activity domains reached the level of healthy controls during the 2-year follow-up.

The screw malpositioning and revision rates are substantially higher when pedicle screws are inserted without intraoperative imaging (Baky et al., 2019; Hicks et al., 2010; Şarlak et al., 2009). In AIS, the screw placement is complicated by spinal deformation in all three dimensions (Şarlak et al., 2009). Although, the small osseous elements of the growing spine complicate the PS placement, their elastic nature allows implantation of screws up to 115% of the pedicle diameter (Suk et al., 2001). A significantly higher screw revision rate in pediatric patients when compared with adult patients has been reported (Larson et al., 2012). Concerning the intraoperative navigation during pedicle screw placement, we hypothesized that advanced intraoperative 3D imaging would reduce PS-related

complications compared to 2D fluoroscopy. In study II, this hypothesis was verified as AIS patients operated under intraoperative 2D navigation had higher rates of PS-related complications and reoperations. Despite the neurological complications in the 2D group, there were no differences in HRQoL data in 6-month or 2-year follow-ups between the study groups suggesting that these measures do not allow detection of minor neurological deficits.

Although PSF with PSI offers adequate coronal restoration in AIS, it appears to offer less power in the restoration and maintenance of TK when compared with traditional hook-and-wire constructs (Cao et al., 2014). In study III, we hypothesized that increased anteroposterior diameter in beam-like rod constructs together with dual-cup PSs would result in improved correction of TK with similar coronal curve correction when compared with sagittal reinforced rods and tulipine screws. Both constructs provided an adequate correction of both, coronal and sagittal deformity. However, no differences in sagittal deformity restoration were found between sagittal reinforced rods and beam-like rods in AIS patients. Our results showed a higher total SRS-24 score in the beam-like rod group than in the sagittal reinforced rod group at a 2-year follow-up. This result was unexpected considering the similar results in curve correction and similar complication rates between the groups. Even with patients with postoperative hypokyphosis, the effect on HRQoL at early or midterm follow-up is unlikely due to the several compensatory mechanisms in AIS patients (Bennett et al., 2013; Legarreta et al., 2014).

The location of main structural curve in AIS is defined by means of Lenke classification (Lenke et al., 2001). In the surgical treatment, the fusion is recommended to include major and minor structural curves. Thus, in patients with thoracolumbar or lumbar scoliosis the spinal fusion extents to lumbar spine, which limits the flexibility in the area. There is evidence that the extent of lumbar spinal fusion has influence on HRQoL in AIS patients undergoing PSF (Ahonen et al 2023). In study IV, we hypothesized that AIS patients with lumbar spinal fusion (Lenke 3,4,5, and 6 scoliosis) scoliosis have decreased HRQoL when compared with patients in whom the spinal fusion is limited to thoracic spine (Lenke 1 and 2). The association between Lenke classification and its curve type, the extent of lumbar spinal fusion and HRQoL was verified as AIS patients with Lenke 5 scoliosis had lower HRQoL than patients with Lenke 1 or 2 scoliosis after 2-years of follow-up. Two years after the initial surgery, patients with Lenke 5 scoliosis had lower scores in the self-image domain of SRS24 when compared with Lenke 2 group. The postoperative satisfaction domain scores were lower in Lenke 5 group when compared with patients with Lenke 1 and 2 scoliosis in the 2-years follow-up. Furthermore, after 6 months of follow-up, lower total and pain domain scores were reported by patients with Lenke 5 scoliosis when compared with patients in Lenke 1 group. Additionally, patients with Lenke 5 and 6 scoliosis had lower total scores in SRS24 after 10-year FU.

6.1 The HRQoL outcomes in adolescent Scheuermann's kyphosis patients treated with posterior spinal fusion

Although conservative methods in the treatment of Scheuermann´s kyphosis can be applied in non-severe cases, surgical treatment is indicated in patients with a thoracic curve greater than 70° to 75°, neurological symptoms or severe refractory pain. Concerning the surgical method, posterior, or anteroposterior spinal fusions are used. In the surgical procedure, posterior column osteotomies are performed in order to shorter the posterior column of the spine and lengthen the anterior spinal column. The posterior spinal fusion is associated with fewer complications compared to anteroposterior approach, and its rates have been increasing in recent years in the operative treatment of SK (Horn et al., 2019; Lee et al., 2006).

In our study, the mean maximal thoracic kyphosis improved from 79° to 55°. This is in line with previous studies (Cobden et al., 2017; Toombs et al., 2018; Tsirikos & Carter, 2021). The mean kyphosis was corrected from 80° to 45° as reported by Cobden et al. In their study of 88 patients with severe thoracic kyphosis, Tsirikos and Carter reported an improvement of mean thoracic kyphosis from 95° to 48° with the successful restoration of coronal and sagittal balance (Tsirikos & Carter, 2021). A common complication involved in the surgical treatment of SK with posterior spinal instrumentation is the recurrence of junctional kyphosis proximally (PJK) above the fused area. PJK can originate from failure in the selection and/or incorporation of the most proximal vertebra, overcorrection of the kyphosis, or disruption of the ligamentum flavum (Denis et al., 2009). Previous research suggests that also a significant mismatch between pelvic incidence and lumbar lordosis (PI-LL > 10°) can increase the risk for PJK (Nasto et al., 2016). In our study population, 18% of the patients developed PJK. In the literature, the prevalence of PJK has been reported to be up to 30% (Cobden et al., 2017; Denis et al., 2009; Nasto et al., 2016). According to the clinical and HRQoL data, all of our PJK patients remained asymptomatic. The effect of PJK on HRQoL has been questioned also in previous research (Glattes et al., 2005). Thus, although the PJK is present in the radiographs it may not have a great impact on patients' life when revision surgery is not needed.

Our study showed that besides decreasing kyphosis magnitude, the surgical treatment significantly improved the HRQoL of patients with Scheuermann´s kyphosis during the 2-year follow-up, as measured with the SRS-24 questionnaire. Improvement was seen in all domains during the follow-up. Toombs et al. reported similar results, with HRQoL improving in pain, self-image, and general activity domains (Toombs et al., 2018). The change in the HRQoL scores also exceeded minimal clinically important difference (MCID), indicating clinically significant results. Green et al. reported smaller kyphotic angles, less pain, and higher postoperative satisfaction after 2-year follow-up in SK patients who chose surgical treatment when compared to SK patients who chose conservative treatments (Green et al., 2020).

According to Petcharaporn et al., higher thoracic kyphosis is associated with increased pain, lower self-image, and decreased function and activity scores in the SRS-24 questionnaire (Petcharaporn et al., 2007). In contrast to AIS, in which pain does not seem to be a major problem for the vast majority of patients, SK patients experience more pain and have lower mental health (Balagué & Pellisé, 2016; Helenius et al., 2019; Lonner et al., 2013). Our results suggest that correcting the spinal deformity surgically with posterior spinal fusion diminishes much of the pain as well as burden associated with self-image and functioning in Scheuermann's kyphosis. Furthermore, it evens the differences in pain and activity, which preoperatively separates the SK patients from healthy subjects.

6.2 Comparison of pedicle screw related complications and re-operations between intraoperative 2D and 3D imaging

Advanced intraoperative 3D imaging reduced pedicle screw-related complications and reoperations when compared with 2D imaging after free-hand pedicle screw placement in AIS surgery. The intraoperative revision rate of the screws in our study was 3.6% in the 3D group and 0.6% in the 2D group. The finding is in line with previous studies. In their study of 404 PS inserted into pedicles of 23 AIS patients, Oba et al reported a screw revision rate was 2.7% under the O-arm navigation (Oba et al., 2018). Larson et al. used a 3D navigation system and intraoperative CT with a screw revision rate of 3.6% in 50 pediatric patients with different spinal deformities (Larson et al., 2012). The different revision rates between 2D and 3D groups in our study may reflect the fact that screw replacement in the 2D group based solely on the change in IONM whereas the replacement in the 3D group was performed on basis of IONM change and 3D imaging.

The reported rate of pedicle screw misplacement-related neurovascular complications in AIS patients is relatively low with an incidence from 0% to 1.3% (Kwan et al., 2021). A neurologic complication occurred in 2.0% of patients in the 2D group in our study. The complications in AIS surgery may become evident only in the mid or long-term follow-up. Kim et al hypothesized a "definite safe zone" (<2 mm), "probable safe zone" (2–4 mm), and "questionable safe zone" (4–8 mm) for medial breaches of PSs (Kim et al., 2004). The moderate PS breaches are mainly asymptomatic, although they can be associated with delayed dural lesions (Floccari et al., 2017; Suh et al., 2019; Wegener et al., 2008). In our study, two patients in the 2D group developed delayed cerebrospinal fluid leak and were reoperated. The reported rate of reoperations per pedicle screw in AIS patients is low with a worldwide rate of 0.2% per screw (Swany et al., 2022). The reoperation ratio per inserted screw in our study was in line with previous data being 0.24% in the 2D group. No patients were reoperated in the O-arm navigation group for screw malposition.

Data from previous studies have shown that the incidence of misplaced pedicle screws and penetration of vertebra cortex is lower in O-arm-based navigation when compared with C-arm-based navigation in different spinal deformity surgeries (Knafo et al., 2018; Liu et al., 2017; Shin et al., 2012; Tajsic et al., 2018). The extent of radiation exposure in 2D

fluoroscopy navigation is largely dependent on the duration of fluoroscopy time, which, in turn, is influenced by factors such as surgical technique, screw density of implants, and the skill of the operating surgeon. According to a recent study conducted by Su et al., the average effective dose of 2D fluoroscopy in AIS surgery was reported to be 0.27 mSv with a fluoroscopy time of 35 seconds (Su et al., 2017). However, it is important to note that while the imaging protocol for O-arm can be adjusted to a pediatric low-dose protocol, the O-arm scans may result in higher radiation exposure compared to intraoperative 2D fluoroscopy (Su et al., 2016, Su et al., 2017). The effective dose with low-dose pediatric O-arm settings is 0.65 mSv and one or two scans per patient is usually required during AIS surgery.

Although the utilization of intraoperative navigation enhances the precision of PS placement, it also entails exposing both young patients and the surgical team to diagnostic radiation. Therefore, when planning the surgery, it is crucial to carefully consider and balance the advantages of enhanced screw placement accuracy with the potential risks associated with increased radiation exposure. Even if their spinal deformity is not being surgically treated, young patients with spinal deformities undergo a higher number of radiological examinations compared to the general population. Estimating the long-term effects of low dose ionizing radiation is challenging. Nevertheless, a dose-dependent association between diagnostic radiation exposure and increased breast cancer mortality among female patients has been observed (Doody et al., 2000).

6.3 Comparison of sagittal balance restoration between beam-like rods and sagittal reinforced rods in the surgical treatment of AIS

AIS patients often have a reduction in thoracic kyphosis compared to healthy individuals and the restoration of sagittal balance has remained challenging in AIS surgery. In addition to patient characteristics, curve type, and surgical method, the successful correction of deformity in AIS depends highly on the biomechanics of rod and pedicle screw instrumentation.

Several factors in the rod design have to be taken into account when balancing between the benefits and complications related to corrective forces: rod diameter, material, and profile. Rod constructs with smaller diameters are a risk factor for postoperative hypokyphosis (Fletcher et al., 2012). In fact, stronger rods have been associated with better TK correction (Liu et al., 2015). However, when rod stiffness is increased, a higher proportional load is transferred to the rod and correspondingly, lower corrective force focuses on vertebrae bone (Ohrt-Nissen et al., 2018). This has been hypothesized to impact bone quality in long-term follow-up and an increased risk for rod fractures (Asher et al., 2007; Bastian et al., 2001). These findings have led to the development of asymmetric rod profiles, such as sagittal reinforced rods and beam-like rods.

In our study, the beam-like and sagittal reinforced rod constructs provided an adequate correction of both coronal and sagittal deformity. However, we found no difference in TK restoration between sagittal reinforced rods and beam-like rod constructs. Therefore, based on our results the increased sagittal strength in beam-like rods did not result in improved TK correction According to previous findings, asymmetric rod profiles achieve similar coronal deformity correction and have advantages in TK restoration compared to standard circular rods. Lastikka et al. found that the use of sagittal reinforced rods provides better TK restoration and a lower risk for postoperative hypokyphosis when compared with circular rods (Lastikka et al., 2019). Ohrt-Nissen et al reported better TK restoration with beam-like and partial beam-like rods when compared with circular rods (Ohrt-Nissen et al., 2017). Partial beam-like rods, in which rods transitions from the beam-like shape into a circular shape in the cranial fusion levels, also result in better TK restoration and maintenance compared to full beam-like rods (Ohrt-Nissen et al., 2017). It has been hypothesized that these partial reinforced rods may reduce the risk of PJK. The coronal deformity correction and loss of TK had a slight negative correlation in our study. This reflects the results from previous studies (Gehrchen et al., 2016; Lastikka et al., 2019; Ohrt-Nissen et al., 2017).

Corrective maneuvers and pedicle screw features have a central role in sagittal balance restoration. The PSs and rods form a single biomechanical construct. Therefore, screw-related factors also have a role in deformity correction. Higher pedicle screw density on the concave side of the spine has been associated with improved TK restoration (Liu et al., 2015). The sagittal reinforced rods are used together with tulipine screws and beam-like rods with dual-cup screws. The tulipine screw positioned at the apex of the deformity (i.e., sagittal adjusting screw), have a fixed head screw and contains a sliding saddle whereas the dual-cup screws contain a locking screw head. We hypothesized that the sagittal adjusting screw provides a biomechanically more stable construct with sagittal reinforced rods at the apical area, allowing enhanced three-dimensional correction compared to dual-cup screws and beam-like rods. Vertebral bone in pediatric patients is elastic which may result into partial screw pullout even when maximum-sized PSs are used. This may further limit the TK restoration. Previous studies have presented overbending the concave rods and posterior segmental distraction as methods to improve TK restoration (Le Navéaux et al., 2017; Mladenov et al., 2011). These methods were used in both study groups.

6.4 Association between Lenke classification, extent of lumbar spinal fusion, and HRQoL after instrumented spinal fusion in AIS

The aim of surgical treatment for AIS is primarily to prevent progression of the curve and secondarily to correct the deformity and to improve cosmetic outcomes. Pain and self-image tend to be worse among AIS patients than in healthy controls (Rushton & Grevitt, 2013a). The literature to date suggests that it is only self-image which consistently differs clinically

between patients and healthy individuals (Rushton & Grevitt, 2013a). The surgical intervention generally improves the HRQoL of AIS patients (Ahonen et al., 2023; Helenius et al., 2019). A review by Rushton and Grevitt suggests that surgery can lead to clinically important improvement in patient self-image after 2-year FU (Rushton & Grevitt, 2013b). Preoperatively, approximately 30% of the AIS patients experience back pain (Helenius et al., 2019; Ramirez et al., 1997). The AIS patients who underwent PSF reported less back pain and had a higher HRQoL in pain, activity, and self-image domains after 5-year FU when compared with patients with untreated AIS (Helenius et al., 2019).

The association between Lenke classification and HRQoL after the instrumented spinal fusion has remained unclear. The lowest instrumented vertebra (LIV) in instrumented spinal fusion is defined by the characteristics of the curve. In patients with thoracolumbar or lumbar AIS, the spinal fusion consists also the lumbar spine, and extents to level of L3 or L4. Patients whose lumbar spines are spared have higher lumbar flexibility compared to those whose fusions extend to either L2, L3, or L4 (Wilk et al., 2006). Overall, the outcomes of surgical treatment of Lenke type 5 AIS are excellent, and demonstrate spontaneous correction of the thoracic curve with good sagittal balance postoperatively (Yoshihara, 2019). Nevertheless, the long-term consequences of the lowest instrumented vertebra choices on HRQoL are partially unknown. A recent study found out that distal LIVs lead to a worsening of back pain after 7 years of FU, with no significant effect on mental component of the HRQoL (Marie-Hardy et al., 2022).

In our study, there was no difference in pain domain between the study groups, however the patient satisfaction was lower in AIS patients with the LIV distal to L1 level. We hypothesized that in addition to the curve location, the decreased flexibility of the lumbar spine leads to lower HRQoL scores in patients with thoracolumbar scoliosis. The preoperative scores of SRS-24 were similar between the study groups. This reflects the possibility that the postoperative differences are associated with the extent of lumbar spinal fusion rather than the type of the curve or surgical approach. Our results showed that after 6-month FU, the total and pain domain scores were lower in the Lenke 5 groups when compared with Lenke 1 group. This difference becomes extinct at the 2-year FU. We hypothesized that this is related to the surgical strategy to address the Lenke 5 curves. In our study, eleven patients with Lenke 5 scoliosis were operated using an anterior (thoracoabdominal) approach and anterior instrumented fusion. Based on previous research, the clinical or radiographic outcomes do not differ between the anterior or posterior spinal fusion (Hirase et al., 2022). The HRQoL does not differ between Lenke 5C patients treated with ASF or PSF (Charalampidis et al., 2021).

In the patients with 10-year follow-up data available, the SRS-24 total score remained at high level during 2-year FU, but then reduced remarkably to the 10-year FU. In the subgroup of patients with 10-year FU, Lenke 5 and 6 patients had lower SRS-24 scores than other study groups. Patients with lumbar fusion extending to L3 or lower had lower HRQoL scores than patients fused to L2 or above after 10-year FU. Reduced lumbar motility has been associated with lower SRS-22 scores for pain, function, satisfaction, and total scores

at 10-year follow-up (Ohashi et al., 2020). The mean reduction rates of spinal mobility have been reported two-fold less in the thoracic fusion compared to those in the thoracic and lumbar fusion (Ohashi et al., 2020).

6.5 Strengths and Limitations

The strengths include a standardized operative and follow-up protocol for all the patients. The data were collected prospectively and in a standardized manner. We assessed the HRQoL with widely used, validated, and standardized questionnaires. Patients with Scheuermann kyphosis were matched with healthy controls with age- and sex. Most patients had a minimum follow-up of 2 years. Clinical, radiographic, and health-related quality of life data was based on a prospective spine register. In all studies, the SRS-24 questionnaire was used to assess the HRQoL of AIS patients. The SRS-24 is the original disease specific HRQoL outcome parameter developed by SRS. The more improved version of the questionnaire is SRS-22r. In study I, we used SRS-22r in healthy controls and SRS-24 in Scheuermann's kyphosis patients. The results of the SRS-24 and SRS-22r similar methods have been compared previously in a similar manner (Helenius et al., 2019; Virkki et al., 2020). However, converting the SRS-24 data to SRS-22r for comparison can result in inaccuracies and therefore decided to use the original questionnaire in the follow-up of the AIS patients in the studies of this thesis. A further limitation in the HRQoL assessment was a lack of generic HRQoL data from questionnaires such as EQ-5D. The generic health measure would have allowed further assess to e.g., mental health aspects in pediatric patients with spinal deformity.

Study I was limited by the fact that Scheuermann´s kyphosis is a relatively rare disease, thus the number of operated patients was relatively small. We did not compare our results with randomized controls for conservative treatment or natural history. The Scheuermann's kyphosis patients in study I were Finnish, whereas the control group was selected from Swedish population register and from the Stockholm County population register (Diarbakerli et al., 2017). Individual (e.g., ethnicity, age and gender) and social factors (e.g., national culture, living conditions, family income and family environment) can affect the HRQoL (Han et al., 2015). The Nordic countries have been emphasized as countries with high standards of living and small social and economic differences (Grøholt et al., 2019). Therefore, we hypothesized, that the different national background between the patients and controls did not cause significant bias in our results.

In study II, CT scans were not routinely available for the 2D group, and therefore, no comparison could be made in the accuracy of the screw placement between the groups. Because of the radiation exposure, postoperative CT scans, particularly in children are often obtained only if a suspicion rises based on plain radiographs and/or postoperative symptoms. Furthermore, we were not able assess the radiation exposure data of the 2D group to compare it with the exposure in the 3D group. In study II, all patients in the 2D group had 2-year FU, and in the 3D group 91% of the patients reached a 2-year follow-up.

In studies II and III, the 2-year FU was not reached in all patients. In study III, all patients in the sagittal reinforced group and 95% in the beam-like group reached a minimum 2-year follow-up. Comparison between the groups in studies II and III should ideally be performed in a randomized clinical trial. The studies have inherent bias since the other group is historical and the other current. To reduce the bias resulting from different overall follow-up times, the radiographic and health-related quality of life were followed at the 2-year follow-up time point when possible. It is possible that the reduced number of reoperations and complications in the 3D group might reflect the learning curve of the surgical team. However, the use of intraoperative 3D imaging revealed a significant number of pedicle screw breaches which were corrected during the index surgery. In study III, the SRR cohort presented at least similar radiographic outcomes to the BLR group, suggesting that the learning curve is not explaining the current findings. In study IV, the limitations included a single surgeon series, and the limited number of the more uncommon Lenke subgroups, especially Lenke 4 scoliosis. The patients were operated with two different approaches (pedicle screw instrumentation, anterior instrumented spinal fusion).

6.6 Future Perspectives

The surgical treatment of pediatric spinal deformities using posterior spinal fusion with pedicle screw instrumentation has been under continuous development during the last decades. Although current methods provide effective correction of the deformity with a low complication and reoperation rates, many areas remain to be improved.

There is still uncertainty regarding whether enhanced surgical techniques yield superior long-term HRQoL outcomes for patients with SK and AIS in several aspects. It remains unclear, what are the long-term functional outcomes of AIS patients. The long-term functional outcomes of AIS patients, particularly related to pulmonary function and mobility, warrant further investigation. Additionally, there is a need for more comprehensive research on the long-term HRQoL outcomes of SK patients treated with posterior spinal fusion, as well as the reoperation rates among those who develop proximal junctional kyphosis.

The precision of pedicle screw placement using conventional freehand technique under intraoperative imaging techniques is restricted due to the limited visual range of the surgeon and unpredictable variables such as variations between individuals and alterations in body position. Whether the accuracy of pedicle screw placement can further be improved using patient-specific intraoperative screw guiding templates or robotics remains to be seen (Kaneyama et al., 2015; Li et al., 2020). The ultimate result of AIS surgery depends not only on the selection of rods but also on various patient factors (such as skeletal maturity and body mass index), on the type of curve, and the surgical approach employed. Future studies should further evaluate methods to enhance thoracic kyphosis restoration. The patient-specific implants bend at the manufacturing stage to patient's unique anatomy could help to minimize the implant weakening and improve the TK restoration. Furthermore, there is an

ongoing randomized clinical study comparing sagittal balance correction with and without posterior column osteotomies (Clinical-Trials.gov, no. NCT05379868).

7 Conclusions

The conclusions of the studies in this thesis are:

1. Instrumented posterior spinal fusion improves the health-related quality of life of Scheuermann's kyphosis patients during the 2-year follow-up. The greatest improvement is observed in the pain and self-image domains. The health-related quality of life in pain and activity domains reaches the level of healthy individuals, while function and self-image remain at a lower level.

2. Intraoperative 3D imaging reduced pedicle screw-related complications and reoperations in adolescents undergoing pedicle screw instrumentation for idiopathic scoliosis as compared with traditional intraoperative fluoroscopic 2D imaging. However, the improved clinical outcome was not reflected by better health-related quality of life at the final follow-up.

3. There were no differences in the coronal or sagittal deformity restoration in adolescent patients who underwent a posterior spinal fusion with sagittal reinforced rods and beam-like rods for adolescent idiopathic scoliosis.

4. Patients with major curve in the thoracolumbar area had lower health-related quality of life as compared with patients having major curve in the thoracic spine. The extent of the lumbar spinal fusion had an association with lower health-related quality of life when lowest instrumented vertebra was at L2 or below.

Acknowledgements

There are several persons who in one way or another reached their helping hand in the completion of this thesis. Without their genuine support and guidance, this thesis would not be a reality.

First, I would like to sincerely thank my supervisor, Professor Ilkka Helenius for his guidance throughout the process of completing my thesis. Your invaluable mentorship and support have been instrumental in my journey towards achieving this goal. Your expertise and knowledge as well as feedback and suggestions have assisted me in enhancing the quality and depth of my work. I have learned a great deal working with you and deeply appreciate how you've contributed to my growth as a researcher and writer. I hope we can work together in the future.

I want to express my gratitude to Ph.D. Antti Saarinen, my friend and the second supervisor for my dissertation. Our interactions have encompassed both, a few formal, and numerous informal discussions related to this thesis. Your brutally honest feedback has not only guided me through the process of writing this dissertation but has also been a driving force in propelling me forward over the past sixteen years.

I want to thank the preliminary examiners Professor Ville Leinonen and Associate Professor Joonas Sirola from the University of Eastern Finland for providing their valuable comments on this thesis. Your atten ability to identify crucial aspects gave me new perspectives and solutions that I might not have discovered without your input. I would also like to thank members of my thesis committee, Sampsa Vanhatalo and Mikko Heinänen from the University of Helsinki.

The publication of the works included in this thesis would not have been possible without the help, support, and clinical knowledge of several co-authors. Many thanks to Matti Ahonen, Elias Diarbakerli, Aron Franzén, Paul Gerdheim, Linda Helenius, Ville Ponkilainen, Arimatias Raitio, and Johanna Syvänen.

I would like to thank the following institutions for providing research funding for this thesis: Clinical Research Institute HUCH, Finnish Research Foundation for Orthopedics and Traumatology, Vappu Uuspää Foundation, and Päivikki and Sakari Sohlberg Foundation.

Warm thanks to my parents Tarja and Harri for your unwavering support. Your encouragement and advise have carried me through my life. Thank you also Pirkko, Lilja, and Hannu, for your continuous support.

Thanks go to friends and fellow students, especially Antti, Eero J., Verneri, Valtteri, Eero V., and Ville. Last, but not least, I want to thank my partner, Suvi. You have made

sacrifices and shown patience when my time was consumed by this project. I am grateful for every day I get to share with you.

Turussa syyskuussa 2023

Eetu Suominen

References

Ahonen, M., Syvänen, J., Helenius, L., Mattila, M., Perokorpi, T., Diarbakerli, E., Gerdhem, P., & Helenius, I. (2023). Back Pain and Quality of Life 10 years after Segmental Pedicle Screw Instrumentation for Adolescent Idiopathic Scoliosis. *Spine*, *40*(8), 665-671. https://doi.org/10.1097/BRS.0000000000004641

Ali, R. M., Green, D. W., & Patel, T. C. (1999). Scheuermann's kyphosis. *Current Opinion in Pediatrics*, *11*(1), 66.

Asher, M. A., Carson, W. L., Hardacker, J. W., Lark, R. G., & Lai, S. M. (2007). The Effect of Arthrodesis, Implant Stiffness, and Time on the Canine Lumbar Spine. *Clinical Spine Surgery*, *20*(8), 549–559. https://doi.org/10.1097/BSD.0b013e31804c98e5

Asher, M., Min Lai, S., Burton, D., & Manna, B. (2003a). Discrimination Validity of the Scoliosis Research Society-22 Patient Questionnaire: Relationship to Idiopathic Scoliosis Curve Pattern and Curve Size. *Spine*, *28*(1), 74.

Asher, M., Min Lai, S., Burton, D., & Manna, B. (2003b). Scoliosis Research Society-22 Patient Questionnaire: Responsiveness to Change Associated With Surgical Treatment. *Spine*, *28*(1), 70–73.

Asher, M., Min Lai, S., Burton, D., & Manna, B. (2003c). The Reliability and Concurrent Validity of the Scoliosis Research Society-22 Patient Questionnaire for Idiopathic Scoliosis. *Spine*, *28*(1), 63.

Aufdermaur, M. (1981). Juvenile Kyphosis (Scheuermann's Disease): Radiography, Histology, and Pathogenesis. *Clinical Orthopaedics and Related Research®*, *154*, 166.

Baky, F. J., Milbrandt, T., Echternacht, S., Stans, A. A., Shaughnessy, W. J., & Larson, A. N. (2019). Intraoperative Computed Tomography–Guided Navigation for Pediatric Spine Patients Reduced Return to Operating Room for Screw Malposition Compared With Freehand/Fluoroscopic Techniques. *Spine Deformity*, *7*(4), 577–581. https://doi.org/10.1016/j.jspd.2018.11.012

Balagué, F., & Pellisé, F. (2016). Adolescent idiopathic scoliosis and back pain. *Scoliosis and Spinal Disorders*, *11*(1), 27. https://doi.org/10.1186/s13013-016-0086-7

Bartley, C. E., Yaszay, B., Bastrom, T. P., Shah, S. A., Lonner, B. S., Asghar, J., Miyanji, F., Samdani, A., & Newton, P. O. (2017). Perioperative and Delayed Major Complications Following Surgical Treatment of Adolescent Idiopathic Scoliosis. *The Journal of Bone and Joint Surgery*, *99*(14), 1206. https://doi.org/10.2106/JBJS.16.01331

Bastian, L., Lange, U., Knop, C., Tusch, G., & Blauth, M. (2001). Evaluation of the mobility of adjacent segments after posterior thoracolumbar fixation: A biomechanical study. *European Spine Journal*, *10*(4), 295–300. https://doi.org/10.1007/s005860100278

Beauchamp, E. C., Lenke, L. G., Cerpa, M., Newton, P. O., Kelly, M. P., Blanke, K. M., & Investigators, H. S. G. I. S. G. (2020). Selecting the "Touched Vertebra" as the

Lowest Instrumented Vertebra in Patients with Lenke Type-1 and 2 Curves: Radiographic Results After a Minimum 5-Year Follow-up. *The Journal of Bone and Joint Surgery*, *102*(22), 1966–1973. https://doi.org/10.2106/JBJS.19.01485

Bennett, J. T., Hoashi, J. S., Ames, R. J., Kimball, J. S., Pahys, J. M., & Samdani, A. F. (2013). The posterior pedicle screw construct: 5-year results for thoracolumbar and lumbar curves: Presented at the 2013 Joint Spine Section Meeting. *Journal of Neurosurgery: Spine*, *19*(6), 658–663. https://doi.org/10.3171/2013.8.SPINE12816

Bernstein, P., Hentschel, S., Platzek, I., Hühne, S., Ettrich, U., Hartmann, A., & Seifert, J. (2014). Thoracal flat back is a risk factor for lumbar disc degeneration after scoliosis surgery. *The Spine Journal*, *14*(6), 925–932. https://doi.org/10.1016/j.spinee.2013.07.426

Bradford, D. S., Ahmed, K. B., Moe, J. H., Winter, R. B., & Lonstein, J. E. (1980). The surgical management of patients with Scheuermann's disease: A review of twenty-four cases managed by combined anterior and posterior spine fusion. *The Journal of Bone and Joint Surgery. American Volume*, *62*(5), 705–712.

Bradford, D. S., Moe, J. H., Montalvo, F. J., & Winter, R. B. (1974). Scheuermann's kyphosis and roundback deformity. Results of Milwaukee brace treatment. *The Journal of Bone and Joint Surgery. American Volume*, *56*(4), 740–758.

Bradford, D. S., Moe, J. H., Montalvo, F. J., & Winter, R. B. (1975). Scheuermann's kyphosis. Results of surgical treatment by posterior spine arthrodesis in twenty-two patients. *The Journal of Bone and Joint Surgery. American Volume*, *57*(4), 439–448.

Cammarata, M., Aubin, C.-É., Wang, X., & Mac-Thiong, J.-M. (2014). Biomechanical Risk Factors for Proximal Junctional Kyphosis: A Detailed Numerical Analysis of Surgical Instrumentation Variables. *Spine*, *39*(8), E500. https://doi.org/10.1097/BRS.0000000000000222

Cao, Y., Xiong, W., & Li, F. (2014). Pedicle Screw Versus Hybrid Construct Instrumentation in Adolescent Idiopathic Scoliosis: Meta-analysis of Thoracic Kyphosis. *Spine*, *39*(13), E800. https://doi.org/10.1097/BRS.0000000000000342

Cawley, D., Dhokia, R., Sales, J., Darwish, N., & Molloy, S. (2020). Ten techniques for improving navigated spinal surgery. *The Bone & Joint Journal*, *102-B*(3), 371–375. https://doi.org/10.1302/0301-620X.102B3.BJJ-2019-1499.R1

Chang, K.-W. (2003). Cantilever bending technique for treatment of large and rigid scoliosis. *Spine*, *28*(21), 2452–2458. https://doi.org/10.1097/01.BRS.0000092063.63315.D5

Chang, M. S., & Lenke, L. G. (2009). Vertebral Derotation in Adolescent Idiopathic Scoliosis. *Operative Techniques in Orthopaedics*, *19*(1), 19–23. https://doi.org/10.1053/j.oto.2009.04.001

Charalampidis, A., Möller, H., & Gerdhem, P. (2021). Anterior versus posterior fusion surgery in idiopathic scoliosis: A comparison of health-related quality of life and radiographic outcomes in Lenke 5C curves - results from the Swedish spine registry. *Journal of Children's Orthopaedics*, *15*(5), 464–471. https://doi.org/10.1302/1863-2548.15.210049

Cho, S. K., Kim, Y. J., & Lenke, L. G. (2015). Proximal Junctional Kyphosis Following Spinal Deformity Surgery in the Pediatric Patient. *Journal of the American Academy of Orthopaedic Surgeons*, *23*(7), 408. https://doi.org/10.5435/JAAOS-D-14-00143

Clément, J.-L., Geoffray, A., Yagoubi, F., Chau, E., Solla, F., Oborocianu, I., & Rampal, V. (2013). Relationship between Thoracic Hypokyphosis, Lumbar Lordosis and

Sagittal Pelvic Parameters in Adolescent Idiopathic Scoliosis. *European Spine Journal*, *22*(11), 2414–2420. https://doi.org/10.1007/s00586-013-2852-z

Cobb, J. R. (1948). Outline for the study of scoliosis. *Instructional Course Lectures AAOS*, *5*, 261–275.

Cobden, A., Albayrak, A., Camurcu, Y., Sofu, H., Tacal, T., & Kaygusuz, M. A. (2017). Posterior-Only Approach with Pedicle Screws for the Correction of Scheuermann's Kyphosis. *Asian Spine Journal*, *11*(4), 513–519. https://doi.org/10.4184/asj.2017.11.4.513

Cochran, T., Irstam, L., & Nachemson, A. (1983). Long-Term Anatomic and Functional Changes in Patients with Adolescent Idiopathic Scoliosis Treated by Harrington Rod Fusion. *Spine*, *8*(6), 576.

Cotrel, Y., & Dubousset, J. (1984). A new technic for segmental spinal osteosynthesis using the posterior approach. *Revue de chirurgie orthopedique et reparatrice de l'appareil moteur*, *70*(6), 489–494.

Cotrel, Y., Dubousset, J., & Guillaumat, M. (1988). New universal instrumentation in spinal surgery. *Clinical Orthopaedics and Related Research*, *227*, 10–23.

Crawford, A. H., Lykissas, M. G., Gao, X., Eismann, E., & Anadio, J. (2013). All-Pedicle Screw Versus Hybrid Instrumentation in Adolescent Idiopathic Scoliosis Surgery: A Comparative Radiographical Study With a Minimum 2-Year Follow-up. *Spine*, *38*(14), 1199–1208. https://doi.org/10.1097/BRS.0b013e31828ce597

Damborg, F., Engell, V., Andersen, M., Kyvik, K. O., & Thomsen, K. (2006). Prevalence, Concordance, and Heritability of Scheuermann Kyphosis Based on a Study of Twins. *The Journal of Bone and Joint Surgery*, *88*(10), 2133–2136. https://doi.org/10.2106/JBJS.E.01302

Danielsson, A. J. (2013). Natural history of adolescent idiopathic scoliosis: A tool for guidance in decision of surgery of curves above 50°. *Journal of Children's Orthopaedics*, *7*(1), 37–41. https://doi.org/10.1007/s11832-012-0462-7

de Jonge, T., Dubousset, J. F., & Illés, T. (2002). Sagittal plane correction in idiopathic scoliosis. *Spine*, *27*(7), 754–760. https://doi.org/10.1097/00007632-200204010-00013

Deacon, P., Archer, I. A., & Dickson, R. A. (1987). The Anatomy of Spinal Deformity: A Biomechanical Analysis. *Orthopedics*, *10*(6), 897–903. https://doi.org/10.3928/0147-7447-19870601-09

Delikaris, A., Wang, X., Boyer, L., Larson, A. N., Ledonio, C. G. T., & Aubin, C.-E. (2018). Implant Density at the Apex Is More Important Than Overall Implant Density for 3D Correction in Thoracic Adolescent Idiopathic Scoliosis Using Rod Derotation and *en bloc* Vertebral Derotation Technique. *Spine*, *43*(11), E639–E647. https://doi.org/10.1097/BRS.0000000000002465

Denis, F., Sun, E. C., & Winter, R. B. (2009). Incidence and Risk Factors for Proximal and Distal Junctional Kyphosis Following Surgical Treatment for Scheuermann Kyphosis: Minimum Five-Year Follow-up. *Spine*, *34*(20), E729. https://doi.org/10.1097/BRS.0b013e3181ae2ab2

Diab, M. G., Franzone, J. M., & Vitale, M. G. (2011). The Role of Posterior Spinal Osteotomies in Pediatric Spinal Deformity Surgery: Indications and Operative Technique. *Journal of Pediatric Orthopaedics*, *31*, S88. https://doi.org/10.1097/BPO.0b013e3181f73bd4

Diab, M., Smith, A. R., Kuklo, T. R., & Spinal Deformity Study Group. (2007). Neural complications in the surgical treatment of adolescent idiopathic scoliosis. *Spine*, *32*(24), 2759–2763. https://doi.org/10.1097/BRS.0b013e31815a5970

Diarbakerli, E., Grauers, A., Danielsson, A., & Gerdhem, P. (2018). Health-Related Quality of Life in Adulthood in Untreated and Treated Individuals with Adolescent or Juvenile Idiopathic Scoliosis. *The Journal of Bone and Joint Surgery*, *100*(10), 811. https://doi.org/10.2106/JBJS.17.00822

Diarbakerli, E., Grauers, A., & Gerdhem, P. (2017). Population-based normative data for the Scoliosis Research Society 22r questionnaire in adolescents and adults, including a comparison with EQ-5D. *European Spine Journal*, *26*(6), 1631–1637. https://doi.org/10.1007/s00586-016-4854-0

Dickson, J. H., Erwin, W. D., & Rossi, D. (1990). Harrington instrumentation and arthrodesis for idiopathic scoliosis. A twenty-one-year follow-up. *The Journal of Bone and Joint Surgery*, *72*(5), 678.

Dickson, RobertA. (1988). The etiology of spinal deformities. *The Lancet*, *331*(8595), 1151–1155. https://doi.org/10.1016/S0140-6736(88)91963-0

Doody, M., Lonstein, J. E., Stovall, M., Hacker, D. G., Luckyanov, N. & Land, C. E. (2000). Breast Cancer Mortality After Diagnostic Radiography: Findings From the U.S. Scoliosis Cohort Study. *Spine*, *25*(16), 2052.

Duval-Beaupère, G., Schmidt, C., & Cosson, P. (1992). A barycentremetric study of the sagittal shape of spine and pelvis: The conditions required for an economic standing position. *Annals of Biomedical Engineering*, *20*(4), 451–462. https://doi.org/10.1007/BF02368136

Edgren, W., & Vainio, S. (1957). Osteochondrosis juvenilis lumbalis. *Acta Chirurgica Scandinavica. Supplementum*, *227*, 1–47.

Edwards, C. C. I., Lenke, L. G., Peelle, M., Sides, B., Rinella, A., & Bridwell, K. H. (2004). Selective Thoracic Fusion for Adolescent Idiopathic Scoliosis with C Modifier Lumbar Curves: 2- to 16-Year Radiographic and Clinical Results. *Spine*, *29*(5), 536. https://doi.org/10.1097/01.BRS.0000109992.22248.77

Fletcher, N. D., Jeffrey, H., Anna, M., Browne, R., & Sucato, D. J. (2012). Residual Thoracic Hypokyphosis After Posterior Spinal Fusion and Instrumentation in Adolescent Idiopathic Scoliosis: Risk Factors and Clinical Ramifications. *Spine*, *37*(3), 200–206. https://doi.org/10.1097/BRS.0b013e318216106c

Floccari, L., Larson, A. N., Stans, A. A., Fogelson, J., & Helenius, I. (2017). Delayed Dural Leak Following Posterior Spinal Fusion for Idiopathic Scoliosis Using All Posterior Pedicle Screw Technique. *Journal of Pediatric Orthopedics*, *37*(7), e415–e420. https://doi.org/10.1097/BPO.0000000000001008

Gehrchen, M., Ohrt-Nissen, S., Hallager, D. W., & Dahl, B. (2016). A Uniquely Shaped Rod Improves Curve Correction in Surgical Treatment of Adolescent Idiopathic Scoliosis. *Spine*, *41*(14), 1139–1145. https://doi.org/10.1097/BRS.0000000000001504

Glattes, R. C., Bridwell, K. H., Lenke, L. G., Kim, Y. J., Rinella, A., & Edwards, C. I. (2005). Proximal Junctional Kyphosis in Adult Spinal Deformity Following Long Instrumented Posterior Spinal Fusion: Incidence, Outcomes, and Risk Factor Analysis. *Spine*, *30*(14), 1643–1649. https://doi.org/10.1097/01.brs.0000169451.76359.49

Green, C., Brown, K., Caine, H., Dieckmann, R. J., & Rathjen, K. E. (2020). Prospective Comparison of Patient-selected Operative Versus Nonoperative Treatment of Scheuermann Kyphosis. *Journal of Pediatric Orthopaedics*, *40*(8), e716. https://doi.org/10.1097/BPO.0000000000001576

Grøholt, E. K., Lyshol, H., Helleve, A., Alver, K., Hagle, M., & Rusås-Heyerdahl, N. (2019). Indicators for health inequality in the Nordic countries. https://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-5621

Gutowski, W. T., & Renshaw, T. S. (1988). Orthotic results in adolescent kyphosis. *Spine*, *13*(5), 485–489. https://doi.org/10.1097/00007632-198805000-00009

Haher, T. R., Gorup, J. M., Shin, T. M., Homel, P., Merola, A. A., Grogan, D. P., Pugh, L., Lowe, T. G., & Murray, M. (1999). Results of the Scoliosis Research Society Instrument for Evaluation of Surgical Outcome in Adolescent Idiopathic Scoliosis: A Multicenter Study of 244 Patients. *Spine*, *24*(14), 1435.

Halm, H., Niemeyer, T., Link, T., & Liljenqvist, U. (2000). Segmental pedicle screw instrumentation in idiopathic thoracolumbar and lumbar scoliosis. *European Spine Journal*, *9*(3), 191–197. https://doi.org/10.1007/s005860000139

Hamill, C. L., Lenke, L. G., Bridwell, K. H., Chapman, M. P., Blanke, K., & Baldus, C. (1996). The Use of Pedicle Screw Fixation to Improve Correction in the Lumbar Spine of Patients With Idiopathic Scoliosis: Is It Warranted? *Spine*, *21*(10), 1241–1249.

Han, J., Xu, Q., Yang, Y., Yao, Z., & Zhang, C. (2015). Evaluation of quality of life and risk factors affecting quality of life in adolescent idiopathic scoliosis. *Intractable & Rare Diseases Research*, *4*(1), 12–16. https://doi.org/10.5582/irdr.2014.01032

Harrington, P. R. (1962). Treatment of Scoliosis: Correction and Internal Fixation by Spine Instrumentation. *JBJS*, *44*(4), 591.

Helenius, I., Remes, V., Yrjönen, T., Ylikoski, M., Schlenzka, D., Helenius, M., & Poussa, M. (2003). Harrington and Cotrel-Dubousset Instrumentation in Adolescent Idiopathic Scoliosis: Long-Term Functional and Radiographic Outcomes. *The Journal of Bone and Joint Surgery*, *85*(12), 2303–2309.

Helenius, L., Diarbakerli, E., Grauers, A., Lastikka, M., Oksanen, H., Pajulo, O., Löyttyniemi, E., Manner, T., Gerdhem, P., & Helenius, I. (2019). Back Pain and Quality of Life After Surgical Treatment for Adolescent Idiopathic Scoliosis at 5-Year Follow-up: Comparison with Healthy Controls and Patients with Untreated Idiopathic Scoliosis. *The Journal of Bone and Joint Surgery*, *101*(16), 1460–1466. https://doi.org/10.2106/JBJS.18.01370

Helgeson, M. D., Shah, S. A., Newton, P. O., Clements, D. H. I., Betz, R. R., Marks, M. C., Bastrom, T., & Group, T. H. S. (2010). Evaluation of Proximal Junctional Kyphosis in Adolescent Idiopathic Scoliosis Following Pedicle Screw, Hook, or Hybrid Instrumentation. *Spine*, *35*(2), 177. https://doi.org/10.1097/BRS.0b013e3181c77f8c

Hicks, J. M., Singla, A., Shen, F. H., & Arlet, V. (2010). Complications of Pedicle Screw Fixation in Scoliosis Surgery: A Systematic Review. *Spine*, *35*(11), E465. https://doi.org/10.1097/BRS.0b013e3181d1021a

Hirase, T., Ling, J. F., Haghshenas, V., Thirumavalavan, J., Dong, D., Hanson, D. S., & Marco, R. A. W. (2022). Anterior versus posterior spinal fusion for Lenke type 5 adolescent idiopathic scoliosis: A systematic review and meta-analysis of comparative studies. *Spine Deformity*, *10*(2), 267–281. https://doi.org/10.1007/s43390-021-00436-x

Hollenbeck, S. M., Glattes, R. C., Asher, M. A., Lai, S. M., & Burton, D. C. (2008). The Prevalence of Increased Proximal Junctional Flexion Following Posterior Instrumentation and Arthrodesis for Adolescent Idiopathic Scoliosis. *Spine*, *33*(15), 1675. https://doi.org/10.1097/BRS.0b013e31817b5bea

Horn, S. R., Poorman, G. W., Tishelman, J. C., Bortz, C. A., Segreto, F. A., Moon, J. Y., Zhou, P. L., Vaynrub, M., Vasquez-Montes, D., Beaubrun, B. M., Diebo, B. G., Vira, S., Raad, M., Sciubba, D. M., Lafage, V., Schwab, F. J., Errico, T. J., & Passias, P. G. (2019). Trends in Treatment of Scheuermann Kyphosis: A Study of

1,070 Cases From 2003 to 2012. *Spine Deformity*, *7*(1), 100–106. https://doi.org/10.1016/j.jspd.2018.06.004

Horne, J. P., Flannery, R., & Usman, S. (2014). Adolescent Idiopathic Scoliosis: Diagnosis and Management. *American Family Physician*, *89*(3), 193–198.

Hresko, M. T. (2013). Idiopathic Scoliosis in Adolescents. *New England Journal of Medicine*, *368*(9), 834–841. https://doi.org/10.1056/NEJMcp1209063

Kaelin, A. J. (2020). Adolescent idiopathic scoliosis: Indications for bracing and conservative treatments. *Annals of Translational Medicine*, *8*(2), 28. https://doi.org/10.21037/atm.2019.09.69

Kaneyama, S., Sugawara, T., & Sumi, M. (2015). Safe and Accurate Midcervical Pedicle Screw Insertion Procedure With the Patient-Specific Screw Guide Template System. *Spine*, *40*(6), E341. https://doi.org/10.1097/BRS.0000000000000772

Karol, L. A. (2001). Effectiveness of Bracing in Male Patients With Idiopathic Scoliosis. *Spine*, *26*(18), 2001.

Killewo, J., Heggenhougen, K., & Quah, S. (2010). *Epidemiology and Demography in Public Health*. Academic Press.

Kim, Y. J., Bridwell, K. H., Lenke, L. G., Kim, J., & Cho, S. K. (2005). Proximal Junctional Kyphosis in Adolescent Idiopathic Scoliosis Following Segmental Posterior Spinal Instrumentation and Fusion: Minimum 5-Year Follow-up. *Spine*, *30*(18), 2045. https://doi.org/10.1097/01.brs.0000179084.45839.ad

Kim, Y. J., Lenke, L. G., Bridwell, K. H., Cho, Y. S., & Riew, K. D. (2004). Free Hand Pedicle Screw Placement in the Thoracic Spine: Is it Safe? *Spine*, *29*(3), 333–342. https://doi.org/10.1097/01.BRS.0000109983.12113.9B

Kim, Y. J., Lenke, L. G., Bridwell, K. H., Kim, J., Cho, S. K., Cheh, G., & Yoon, J. (2007). Proximal Junctional Kyphosis in Adolescent Idiopathic Scoliosis After 3 Different Types of Posterior Segmental Spinal Instrumentation and Fusions: Incidence and Risk Factor Analysis of 410 Cases. *Spine*, *32*(24), 2731. https://doi.org/10.1097/BRS.0b013e31815a7ead

King, H. A., Moe, J. H., Bradford, D. S., & Winter, R. B. (1983). The Selection of Fusion Levels in Thoracic Idiopathic Scoliosis. *The Journal of Bone and Joint Surgery*, *65*(9), 1302.

Knafo, S., Mireau, E., Bennis, S., Baussart, B., Aldea, S., & Gaillard, S. (2018). Operative and Perioperative Durations in O-Arm vs C-Arm Fluoroscopy for Lumbar Instrumentation. *Operative Neurosurgery*, *14*(3), 273–278. https://doi.org/10.1093/ons/opx142

Koller, H., Juliane, Z., Umstaetter, M., Meier, O., Schmidt, R., & Hitzl, W. (2014). Surgical Treatment of Scheuermann's Kyphosis Using a Combined Antero-Posterior Strategy and Pedicle Screw Constructs: Efficacy, Radiographic and Clinical Outcomes in 111 Cases. *European Spine Journal*, *23*(1), 180–191. https://doi.org/10.1007/s00586-013-2894-2

Koptan, W. M. T., Elmiligui, Y. H., & Elsebaie, H. B. (2009). All Pedicle Screw Instrumentation for Scheuermann's Kyphosis Correction: Is it worth it? *The Spine Journal*, *9*(4), 296–302. https://doi.org/10.1016/j.spinee.2008.05.011

Kwan, M. K., Loh, K. W., Chung, W. H., Chiu, C. K., Hasan, M. S., & Chan, C. Y. W. (2021). Perioperative outcome and complications following single-staged Posterior Spinal Fusion (PSF) using pedicle screw instrumentation in Adolescent Idiopathic Scoliosis (AIS): A review of 1057 cases from a single centre. *BMC Musculoskeletal Disorders*, *22*(1), 413. https://doi.org/10.1186/s12891-021-04225-5

Labrom, F. R., Izatt, M. T., Claus, A. P., & Little, J. P. (2021). Adolescent idiopathic scoliosis 3D vertebral morphology, progression and nomenclature: A current concepts review. *European Spine Journal*, *30*(7), 1823–1834. https://doi.org/10.1007/s00586-021-06842-z

Larson, A. N., Santos, E. R. G., Polly, D. W. J., Ledonio, C. G. T., Sembrano, J. N., Mielke, C. H., & Guidera, K. J. (2012). Pediatric Pedicle Screw Placement Using Intraoperative Computed Tomography and 3-Dimensional Image-Guided Navigation. *Spine*, *37*(3), E188. https://doi.org/10.1097/BRS.0b013e31822a2e0a

Lastikka, M., Oksanen, H., Helenius, L., Pajulo, O., & Helenius, I. (2019). Comparison of Circular and Sagittal Reinforced Rod Options on Sagittal Balance Restoration in Adolescents Undergoing Pedicle Screw Instrumentation for Idiopathic Scoliosis. *World Neurosurgery*, *127*, e1020–e1025. https://doi.org/10.1016/j.wneu.2019.04.028

Le Navéaux, F., Aubin, C.-E., Parent, S., O. Newton, P., & Labelle, H. (2017). 3D rod shape changes in adolescent idiopathic scoliosis instrumentation: How much does it impact correction? *European Spine Journal*, *26*(6), 1676–1683. https://doi.org/10.1007/s00586-017-4958-1

Ledonio, C. G. T., Polly, D. W. J., Vitale, M. G., Wang, Q., & Richards, B. S. (2011). Pediatric Pedicle Screws: Comparative Effectiveness and Safety: A Systematic Literature Review from the Scoliosis Research Society and the Pediatric Orthopaedic Society of North America Task Force. *The Journal of Bone and Joint Surgery*, *93*(13), 1227–1234. https://doi.org/10.2106/JBJS.J.00678

Lee, G. A., Betz, R. R., Clements, D. H. I., & Huss, G. K. (1999). Proximal Kyphosis After Posterior Spinal Fusion in Patients With Idiopathic Scoliosis. *Spine*, *24*(8), 795.

Lee, S. S., Lenke, L. G., Kuklo, T. R., Valenté, L., Bridwell, K. H., Sides, B., & Blanke, K. M. (2006). Comparison of Scheuermann Kyphosis Correction by Posterior-Only Thoracic Pedicle Screw Fixation Versus Combined Anterior/Posterior Fusion. *Spine*, *31*(20), 2316–2321. https://doi.org/10.1097/01.brs.0000238977.36165.b8

Legarreta, C. A., Barrios, C., Rositto, G. E., Reviriego, J. M., Maruenda, J. I., Escalada, M. N., Piza-Vallespir, G., Burgos, J., & Hevia, E. (2014). Cervical and Thoracic Sagittal Misalignment After Surgery for Adolescent Idiopathic Scoliosis: A Comparative Study of All Pedicle Screws Versus Hybrid Instrumentation. *Spine*, *39*(16), 1330. https://doi.org/10.1097/BRS.0000000000000403

Lenke, L. G., Betz, R. R., Harms, J., Bridwell, K. H., Clements, D. H., Lowe, T. G., & Blanke, K. (2001). Adolescent Idiopathic Scoliosis: A New Classification to Determine Extent of Spinal Arthrodesis. *The Journal of Bone and Joint Surgery*, *83*(8), 1169–1181.

Li, H.-M., Zhang, R.-J., & Shen, C.-L. (2020). Accuracy of Pedicle Screw Placement and Clinical Outcomes of Robot-assisted Technique Versus Conventional Freehand Technique in Spine Surgery From Nine Randomized Controlled Trials: A Meta-analysis. *Spine*, *45*(2), E111. https://doi.org/10.1097/BRS.0000000000003193

Liljenqvist, U. R., Halm, H. F. H., & Link, T. M. (1997). Pedicle Screw Instrumentation of the Thoracic Spine in Idiopathic Scoliosis. *Spine*, *22*(19), 2239.

Liu, H., Li, Z., Li, S., Zhang, K., Yang, H., Wang, J., Li, X., & Zheng, Z. (2015). Main thoracic curve adolescent idiopathic scoliosis: Association of higher rod stiffness and concave-side pedicle screw density with improvement in sagittal thoracic kyphosis restoration. *Journal of Neurosurgery: Spine*, *22*(3), 259–266. https://doi.org/10.3171/2014.10.SPINE1496

Liu, H., Wang, Y., Pi, B., Qian, Z., Zhu, X., & Yang, H. (2017). Comparison of intraoperative O-arm- and conventional fluoroscopy (C-arm)-assisted insertion of pedicle screws in the treatment of fracture of thoracic vertebrae. *Journal of Orthopaedic Surgery*, *25*(1), 2309499016684090. https://doi.org/10.1177/2309499016684090

Lonner, B. S., Newton, P., Betz, R., Scharf, C., O'Brien, M., Sponseller, P., Lenke, L., Crawford, A., Lowe, T., Letko, L., Harms, J., & Shufflebarger, H. (2007). Operative Management of Scheuermann's Kyphosis in 78 Patients: Radiographic Outcomes, Complications, and Technique. *Spine*, *32*(24), 2644. https://doi.org/10.1097/BRS.0b013e31815a5238

Lonner, B. S., Ren, Y., Newton, P. O., Shah, S. A., Samdani, A. F., Shufflebarger, H. L., Asghar, J., Sponseller, P., Betz, R. R., & Yaszay, B. (2017). Risk Factors of Proximal Junctional Kyphosis in Adolescent Idiopathic Scoliosis—The Pelvis and Other Considerations. *Spine Deformity*, *5*(3), 181–188. https://doi.org/10.1016/j.jspd.2016.10.003

Lonner, B. S., Toombs, C. S., Guss, M., Braaksma, B., Shah, S. A., Samdani, A., Shufflebarger, H., Sponseller, P., & Newton, P. O. (2015). Complications in Operative Scheuermann Kyphosis: Do the Pitfalls Differ From Operative Adolescent Idiopathic Scoliosis? *Spine*, *40*(5), 305. https://doi.org/10.1097/BRS.0000000000000757

Lonner, B., Yoo, A., Terran, J. S., Sponseller, P., Samdani, A., Betz, R., Shuffelbarger, H., Shah, S. A., & Newton, P. (2013). Effect of Spinal Deformity on Adolescent Quality of Life: Comparison of Operative Scheuermann Kyphosis, Adolescent Idiopathic Scoliosis, and Normal Controls. *Spine*, *38*(12), 1049–1055. https://doi.org/10.1097/BRS.0b013e3182893c01

Lonstein, J. E., & Winter, R. B. (1994). The Milwaukee brace for the treatment of adolescent idiopathic scoliosis. A review of one thousand and twenty patients. *The Journal of Bone and Joint Surgery*, *76*(8), 1207.

Lowe, T. G., & Kasten, M. D. (1994). An analysis of sagittal curves and balance after Cotrel-Dubousset instrumentation for kyphosis secondary to Scheuermann's disease. A review of 32 patients. *Spine*, *19*(15), 1680–1685. https://doi.org/10.1097/00007632-199408000-00005

Lowenstein, J. E., Matsumoto, H., Vitale, M. G., Weidenbaum, M., Gomez, J. A., Lee, F. Y.-I., Hyman, J. E., & Roye, D. P. J. (2007). Coronal and Sagittal Plane Correction in Adolescent Idiopathic Scoliosis: A Comparison Between All Pedicle Screw: Versus: Hybrid Thoracic Hook Lumbar Screw Constructs. *Spine*, *32*(4), 448. https://doi.org/10.1097/01.brs.0000255030.78293.fd

Luk, K. D. K., Lee, C. F., Cheung, K. M. C., Cheng, J. C. Y., Ng, B. K. W., Lam, T. P., Mak, K. H., Yip, P. S. F., & Fong, D. Y. T. (2010). Clinical Effectiveness of School Screening for Adolescent Idiopathic Scoliosis: A Large Population-Based Retrospective Cohort Study. *Spine*, *35*(17), 1607. https://doi.org/10.1097/BRS.0b013e3181c7cb8c

Luo, M., Jiang, H., Wang, W., Li, N., Shen, M., Li, P., Xu, G., & Xia, L. (2017). Influence of screw density on thoracic kyphosis restoration in hypokyphotic adolescent idiopathic scoliosis. *BMC Musculoskeletal Disorders*, *18*(1), 526. https://doi.org/10.1186/s12891-017-1877-6

Marie-Hardy, L., Besse, M., Chatelain, L., Pannier, S., Glorion, C., & Ferrero, E. (2022). Does the Distal Level Really Matter in the Setting of Health-Related Quality of Life? Assessment of a Series of Adolescent Idiopathic Scoliosis Patients at More Than 7 Years Following Surgery. *Spine*, *47*(16), E545. https://doi.org/10.1097/BRS.0000000000004315

Matsumoto, T., Kitahara, H., Minami, S., Takahashi, K., Yamagata, M., Moriya, H., & Tamaki, T. (1997). Flexibility in the scoliotic spine: Three-dimensional analysis. *Journal of Spinal Disorders*, *10*(2), 125–131.

Matsunaga, S., Hayashi, K., Naruo, T., Nozoe, S., & Komiya, S. (2005). Psychologic Management of Brace Therapy for Patients With Idiopathic Scoliosis. *Spine*, *30*(5), 547. https://doi.org/10.1097/01.brs.0000154648.53535.52

Mattila, M., Jalanko, T., & Helenius, I. (2013). En Bloc Vertebral Column Derotation Provides Spinal Derotation But No Additional Effect on Thoracic Rib Hump Correction as Compared With No Derotation in Adolescents Undergoing Surgery for Idiopathic Scoliosis With Total Pedicle Screw Instrumentation. *Spine*, *38*(18), 1576–1583. https://doi.org/10.1097/BRS.0b013e31829a6d37

Mens, R. H., Bisseling, P., Kleuver, M. de, & Hooff, M. L. van. (2022). Relevant impact of surgery on quality of life for adolescent idiopathic scoliosis: A registry-based two-year follow-up cohort study. *The Bone & Joint Journal*, *104-B*(2), 265–273. https://doi.org/10.1302/0301-620X.104B2.BJJ-2021-1179.R1

Mladenov, K. V., Vaeterlein, C., & Stuecker, R. (2011). Selective posterior thoracic fusion by means of direct vertebral derotation in adolescent idiopathic scoliosis: Effects on the sagittal alignment. *European Spine Journal: Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*, *20*(7), 1114–1117. https://doi.org/10.1007/s00586-011-1740-7

Montgomery, S. P., & Erwin, W. E. (1981). Scheuermann's Kyphosis—Long-Term Results of Milwaukee Brace Treatment. *Spine*, *6*(1), 5.

Murray, P. M., Weinstein, S. L., & Spratt, K. F. (1993). The natural history and long-term follow-up of Scheuermann kyphosis. *The Journal of Bone and Joint Surgery American Volume*, *75*(2), 236–248. https://doi.org/10.2106/00004623-199302000-00011

Nachemson, A. L., & Peterson, L. E. (1995). Effectiveness of treatment with a brace in girls who have adolescent idiopathic scoliosis. A prospective, controlled study based on data from the Brace Study of the Scoliosis Research Society. *The Journal of Bone and Joint Surgery*, *77*(6), 815.

Nasto, L. A., Perez-Romera, A. B., Shalabi, S. T., Quraishi, N. A., & Mehdian, H. (2016). Correlation between preoperative spinopelvic alignment and risk of proximal junctional kyphosis after posterior-only surgical correction of Scheuermann kyphosis. *The Spine Journal*, *16*(4, Supplement), S26–S33. https://doi.org/10.1016/j.spinee.2015.12.100

Newton, P. O., Faro, F. D., Gollogly, S., Betz, R. R., Lenke, L. G., & Lowe, T. G. (2005). Results of Preoperative Pulmonary Function Testing of Adolescents with Idiopathic Scoliosis: A Study of Six Hundred and Thirty-one Patients. *The Journal of Bone and Joint Surgery*, *87*(9), 1937–1946. https://doi.org/10.2106/JBJS.D.02209

Oba, H., Ebata, S., Takahashi, J., Koyama, K., Uehara, M., Kato, H., Haro, H., & Ohba, T. (2018). Pedicle Perforation While Inserting Screws Using O-arm Navigation During Surgery for Adolescent Idiopathic Scoliosis: Risk Factors and Effect of Insertion Order. *Spine*, *43*(24), E1463. https://doi.org/10.1097/BRS.0000000000002737

Ohashi, M., Bastrom, T. P., Marks, M. C., Bartley, C. E., & Newton, P. O. (2020). The Benefits of Sparing Lumbar Motion Segments in Spinal Fusion for Adolescent Idiopathic Scoliosis Are Evident at 10 Years Postoperatively. *Spine*, *45*(11), 755. https://doi.org/10.1097/BRS.0000000000003373

Ohrt-Nissen, S., Dahl, B., & Gehrchen, M. (2018). Choice of Rods in Surgical Treatment of Adolescent Idiopathic Scoliosis: What Are the Clinical Implications of Biomechanical Properties? – A Review of the Literature. *Neurospine*, *15*(2), 123–130. https://doi.org/10.14245/ns.1836050.025

Ohrt-Nissen, S., Dragsted, C., Dahl, B., Ferguson, J. A. I., & Gehrchen, M. (2017). Improved restoration of thoracic kyphosis using a rod construct with differentiated rigidity in the surgical treatment of adolescent idiopathic scoliosis. *Neurosurgical Focus*, *43*(4), E6. https://doi.org/10.3171/2017.7.FOCUS17351

Olafsson, Y., Saraste, H., Söderlund, V., & Hoffsten, M. (1995). Boston Brace in the Treatment of Idiopathic Scoliosis. *Journal of Pediatric Orthopaedics*, *15*(4), 524.

Palazzo, C., Sailhan, F., & Revel, M. (2014). Scheuermann's disease: An update. *Joint Bone Spine*, *81*(3), 209–214. https://doi.org/10.1016/j.jbspin.2013.11.012

Parent, E. C., Hill, D., Mahood, J., Moreau, M., Raso, J., & Lou, E. (2009). Discriminative and Predictive Validity of the Scoliosis Research Society-22 Questionnaire in Management and Curve-Severity Subgroups of Adolescents With Idiopathic Scoliosis. *Spine*, *34*(22), 2450. https://doi.org/10.1097/BRS.0b013e3181af28bf

Parent, E. C., Wong, D., Hill, D., Mahood, J., Moreau, M., Raso, V. J., & Lou, E. (2010). The Association Between Scoliosis Research Society-22 Scores and Scoliosis Severity Changes at a Clinically Relevant Threshold. *Spine*, *35*(3), 315. https://doi.org/10.1097/BRS.0b013e3181cabe75

Pehrsson, K., Larsson, S., Oden, A., & Nachemson, A. (1992). Long-Term Follow-Up of Patients with Untreated Scoliosis A Study of Mortality, Causes of Death, and Symptoms. *Spine*, *17*(9), 1091.

Petcharaporn, M., Pawelek, J., Bastrom, T., Lonner, B., & Newton, P. O. (2007). The Relationship Between Thoracic Hyperkyphosis and the Scoliosis Research Society Outcomes Instrument. *Spine*, *32*(20), 2226–2231. https://doi.org/10.1097/BRS.0b013e31814b1bef

Ponte, A., Orlando, G., & Siccardi, G. L. (2018). The True Ponte Osteotomy: By the One Who Developed It. *Spine Deformity*, *6*(1), 2–11. https://doi.org/10.1016/j.jspd.2017.06.006

Potter, B. K., Lenke, L. G., & Kuklo, T. R. (2004). Prevention and Management of Iatrogenic Flatback Deformity. *JBJS*, *86*(8), 1793.

Quan, G. M. Y., & Gibson, M. J. (2010). Correction of main thoracic adolescent idiopathic scoliosis using pedicle screw instrumentation: Does higher implant density improve correction? *Spine*, *35*(5), 562–567. https://doi.org/10.1097/BRS.0b013e3181b4af34

Ra, H. (1911). An operation for progressive spinal deformities. A preliminary report of three cases from the service of the Orthopaedic hospital. *NY Med J*, *93*, 1013–1016.

Ragborg, L., Dragsted, C., Dahl, B., & Gehrchen, M. (2020). Scheuermann's Kyphosis: A 39-year follow-up from diagnosis in non-operated patients. *European Spine Journal*, *29*(8), 2091–2099. https://doi.org/10.1007/s00586-020-06384-w

Ramirez, N., Johnston, C. E. I., & Browne, R. H. (1997). The Prevalence of Back Pain in Children Who Have Idiopathic Scoliosis*. *JBJS*, *79*(3), 364.

Reames, D. L., Smith, J. S., Fu, K.-M. G., Polly, D. W., Ames, C. P., Berven, S. H., Perra, J. H., Glassman, S. D., McCarthy, R. E., Knapp, R. D., Heary, R., Shaffrey, C. I., & Scoliosis Research Society Morbidity and Mortality Committee. (2011). Complications in the surgical treatment of 19,360 cases of pediatric scoliosis: A

review of the Scoliosis Research Society Morbidity and Mortality database. *Spine*, *36*(18), 1484–1491. https://doi.org/10.1097/BRS.0b013e3181f3a326

Rhee, J. M., Bridwell, K. H., Won, D. S., Lenke, L. G., Chotigavanichaya, C., & Hanson, D. S. (2002). Sagittal Plane Analysis of Adolescent Idiopathic Scoliosis: The Effect of Anterior: Versus: Posterior Instrumentation. *Spine*, *27*(21), 2350.

Ristolainen, L., Kettunen, J. A., Heliövaara, M., Kujala, U. M., Heinonen, A., & Schlenzka, D. (2012). Untreated Scheuermann's disease: A 37-year follow-up study. *European Spine Journal*, *21*(5), 819–824. https://doi.org/10.1007/s00586-011-2075-0

Ritzman, T. F., Upasani, V. V., Bastrom, T. P., Betz, R. R., Lonner, B. S., & Newton, P. O. (2008). Comparison of Compensatory Curve Spontaneous Derotation After Selective Thoracic or Lumbar Fusions in Adolescent Idiopathic Scoliosis. *Spine*, *33*(24), 2643. https://doi.org/10.1097/BRS.0b013e3181891806

Rowe, D. E., Bernstein, S. M., Riddick, M. F., Adler, F., Emans, J. B., & Gardner-Bonneau, D. (1997). A Meta-Analysis of the Efficacy of Non-Operative Treatments for Idiopathic Scoliosis*†. *JBJS*, *79*(5), 664.

Rushton, P. R. P., & Grevitt, M. P. (2013a). Comparison of Untreated Adolescent Idiopathic Scoliosis With Normal Controls: A Review and Statistical Analysis of the Literature. *Spine*, *38*(9), 778–785. https://doi.org/10.1097/BRS.0b013e31827db418

Rushton, P. R. P., & Grevitt, M. P. (2013b). What Is the Effect of Surgery on the Quality of Life of the Adolescent With Adolescent Idiopathic Scoliosis?: A Review and Statistical Analysis of the Literature. *Spine*, *38*(9), 786. https://doi.org/10.1097/BRS.0b013e3182837c95

Sachs, B., Bradford, D., Winter, R., Lonstein, J., Moe, J., & Willson, S. (1987). Scheuermann kyphosis. Follow-up of Milwaukee-brace treatment. *JBJS*, *69*(1), 50.

Santos, E. R. G., Ledonio, C. G., Castro, C. A., Truong, W. H., & Sembrano, J. N. (2012). The Accuracy of Intraoperative O-arm Images for the Assessment of Pedicle Screw Postion. *Spine*, *37*(2), E119. https://doi.org/10.1097/BRS.0b013e3182257cae

Şarlak, A. Y., Tosun, B., Atmaca, H., Sarisoy, H. T., & Buluç, L. (2009). Evaluation of thoracic pedicle screw placement in adolescent idiopathic scoliosis. *European Spine Journal*, *18*(12), 1892. https://doi.org/10.1007/s00586-009-1065-y

Scheuermann, H. W. (1977). Kyphosis Dorsalis Juvenilis. *Clinical Orthopaedics and Related Research (1976-2007)*, *128*, 5.

Shah, S. A. (2007). Derotation of the Spine. *Neurosurgery Clinics of North America*, *18*(2), 339–345. https://doi.org/10.1016/j.nec.2007.02.003

Shah, S. A., Dhawale, A. A., Oda, J. E., Yorgova, P., Neiss, G. I., Holmes, L., & Gabos, P. G. (2013). Ponte Osteotomies With Pedicle Screw Instrumentation in the Treatment of Adolescent Idiopathic Scoliosis. *Spine Deformity*, *1*(3), 196–204. https://doi.org/10.1016/j.jspd.2013.03.002

Shin, M.-H., Ryu, K.-S., & Park, C.-K. (2012). Accuracy and Safety in Pedicle Screw Placement in the Thoracic and Lumbar Spines: Comparison Study between Conventional C-Arm Fluoroscopy and Navigation Coupled with O-Arm® Guided Methods. *Journal of Korean Neurosurgical Society*, *52*(3), 204–209. https://doi.org/10.3340/jkns.2012.52.3.204

Smith-Petersen, M. N., Larson, C. B., & Aufranc, O. E. (1945). OSTEOTOMY OF THE SPINE FOR CORRECTION OF FLEXION DEFORMITY IN RHEUMATOID ARTHRITIS. *JBJS*, *27*(1), 1.

Sorenson, K. (1964). *Scheuermann's Juvenile Kyphosis: Clinical Appearances, Radiography, Aetiology, and Prognosis*. Munksgaard.

Su, A. W., Luo, T. D., McIntosh, A. L., Schueler, B. A., Winkler, J. A., Stans, A. A., & Larson, A. N. (2016). Switching to a Pediatric Dose O-Arm Protocol in Spine Surgery Significantly Reduced Patient Radiation Exposure. *Journal of Pediatric Orthopaedics*, *36*(6), 621–626. https://doi.org/10.1097/BPO.0000000000000504

Su, A. W., McIntosh, A. L., Schueler, B. A., Milbrandt, T. A., Winkler, J. A., Stans, A. A., & Larson, A. N. (2017). How Does Patient Radiation Exposure Compare With Low-dose O-arm Versus Fluoroscopy for Pedicle Screw Placement in Idiopathic Scoliosis? *Journal of Pediatric Orthopaedics*, *37*(3), 171–177. https://doi.org/10.1097/BPO.0000000000000608

Sud, A., & Tsirikos, A. I. (2013). Current concepts and controversies on adolescent idiopathic scoliosis: Part I. *Indian Journal of Orthopaedics*, *47*(2), 117–128. https://doi.org/10.4103/0019-5413.108875

Sudo, H., Abe, Y., Kokabu, T., Ito, M., Abumi, K., Ito, Y. M., & Iwasaki, N. (2016). Correlation analysis between change in thoracic kyphosis and multilevel facetectomy and screw density in main thoracic adolescent idiopathic scoliosis surgery. *The Spine Journal*, *16*(9), 1049–1054. https://doi.org/10.1016/j.spinee.2016.04.014

Suh, S.-W., Kim, G.-U., Lee, H.-N., Yang, J. H., & Chang, D.-G. (2019). Delayed presentation of infected common iliac artery pseudoaneurysm caused by malpositioned pedicle screw after minimally invasive scoliosis surgery. *European Spine Journal*, *28*(2), 68–72. https://doi.org/10.1007/s00586-019-06005-1

Suk, S. I., Kim, W. J., Lee, S. M., Kim, J. H., & Chung, E. R. (2001). Thoracic pedicle screw fixation in spinal deformities: Are they really safe? *Spine*, *26*(18), 2049–2057. https://doi.org/10.1097/00007632-200109150-00022

Suk, S., Lee, C. K., Kim, W.-J., Chung, Y.-J., & Park, Y.-B. (1995). Segmental Pedicle Screw Fixation in the Treatment of Thoracic Idiopathic Scoliosis. *Spine*, *20*(12), 1399.

Suk, S.-I., Kim, J.-H., Kim, S.-S., & Lim, D.-J. (2012). Pedicle screw instrumentation in adolescent idiopathic scoliosis (AIS). *European Spine Journal*, *21*(1), 13–22. https://doi.org/10.1007/s00586-011-1986-0

Suk, S.-I., Kim, W.-J., Lee, S.-M., Kim, J.-H., & Chung, E.-R. (2001). Thoracic Pedicle Screw Fixation in Spinal Deformities: Are They Really Safe? *Spine*, *26*(18), 2049–2057.

Swany, L., Larson, A. N., Garg, S., Hedequist, D., Newton, P., Sponseller, P., & Harms Study Group. (2022). 0.4% incidence of return to OR due to screw malposition in a large prospective adolescent idiopathic scoliosis database. *Spine Deformity*, *10*(2), 361–367. https://doi.org/10.1007/s43390-021-00434-z

Tajsic, T., Patel, K., Farmer, R., Mannion, R. J., & Trivedi, R. A. (2018). Spinal navigation for minimally invasive thoracic and lumbosacral spine fixation: Implications for radiation exposure, operative time, and accuracy of pedicle screw placement. *European Spine Journal*, *27*(8), 1918–1924. https://doi.org/10.1007/s00586-018-5587-z

Tones, M., Moss, N., & Polly, D. W. J. (2006). A Review of Quality of Life and Psychosocial Issues in Scoliosis. *Spine*, *31*(26), 3027. https://doi.org/10.1097/01.brs.0000249555.87601.fc

Toombs, C., Lonner, B., Shah, S., Samdani, A., Cahill, P., Shufflebarger, H., Yaszay, B., Sponseller, P., & Newton, P. (2018). Quality of Life Improvement Following Surgery in Adolescent Spinal Deformity Patients: A Comparison Between

Scheuermann Kyphosis and Adolescent Idiopathic Scoliosis*. *Spine Deformity*, *6*(6), 676–683. https://doi.org/10.1016/j.jspd.2018.04.009

Trobisch, P. D., Ducoffe, A. R., Lonner, B. S., & Errico, T. J. (2013). Choosing Fusion Levels in Adolescent Idiopathic Scoliosis. *JAAOS - Journal of the American Academy of Orthopaedic Surgeons*, *21*(9), 519. https://doi.org/10.5435/JAAOS-21-09-519

Tsirikos, A. I., & Carter, T. H. (2021). The surgical treatment of severe Scheuermann's kyphosis. *The Bone & Joint Journal*, *103-B*(1), 148–156. https://doi.org/10.1302/0301-620X.103B1.BJJ-2020-1279.R2

Ueno, M., Takaso, M., Nakazawa, T., Imura, T., Saito, W., Shintani, R., Uchida, K., Fukuda, M., Takahashi, K., Ohtori, S., Kotani, T., & Minami, S. (2011). A 5-year epidemiological study on the prevalence rate of idiopathic scoliosis in Tokyo: School screening of more than 250,000 children. *Journal of Orthopaedic Science*, *16*(1), 1–6. https://doi.org/10.1007/s00776-010-0009-z

van Linthoudt, D., & Revel, M. (1994). Similar Radiologic Lesions of Localized Scheuermann's Disease of the Lumbar Spine in Twin Sisters. *Spine*, *19*(8), 987.

Virkki, E. N., Oksanen, H., Diarbakerli, E., Helenius, L., Pape, B., Pajulo, O., Gerdhem, P., & Helenius, I. (2020). Health-Related Quality of Life Outcomes of Instrumented Circumferential Spinal Fusion for Pediatric Spondylolisthesis: A Comparison With Age and Sex Matched Healthy Controls. *Spine*, *45*(23), E1572. https://doi.org/10.1097/BRS.0000000000003681

Watanabe, K., Ohashi, M., Hirano, T., Katsumi, K., Mizouchi, T., Tashi, H., Minato, K., Hasegawa, K., & Endo, N. (2020). Health-Related Quality of Life in Nonoperated Patients With Adolescent Idiopathic Scoliosis in the Middle Years: A Mean 25-Year Follow-up Study. *Spine*, *45*(2), E83. https://doi.org/10.1097/BRS.0000000000003216

Webb, J. K., Burwell, R. G., Cole, A. A., & Lieberman, I. (1995). Posterior instrumentation in scoliosis. *European Spine Journal: Official Publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*, *4*(1), 2–5. https://doi.org/10.1007/BF00298409

Wegener, B., Birkenmaier, C., Fottner, A., Jansson, V., & Dürr, H. R. (2008). Delayed perforation of the aorta by a thoracic pedicle screw. *European Spine Journal*, *17*(2), 351–354. https://doi.org/10.1007/s00586-008-0715-9

Weiss, H.R., Dieckmann, J., & Gerner, H.J. (2002). Effect of Intensive Rehabilitation on Pain in Patients with Scheuermann's Disease. *Research into Spinal Deformities 3*, 254–257. https://doi.org/10.3233/978-1-60750-932-5-254

Weinstein, S. L. (1989). Adolescent idiopathic scoliosis: Prevalence and natural history. *Instructional Course Lectures*, *38*, 115–128.

Weinstein, S. L. (2019). The Natural History of Adolescent Idiopathic Scoliosis. *Journal of Pediatric Orthopaedics*, *39*, S44. https://doi.org/10.1097/BPO.0000000000001350

Weinstein, S. L., Dolan, L. A., Cheng, J. C., Danielsson, A., & Morcuende, J. A. (2008). Adolescent idiopathic scoliosis. *The Lancet*, *371*(9623), 1527–1537. https://doi.org/10.1016/S0140-6736(08)60658-3

Weinstein, S. L., Dolan, L. A., Wright, J. G., & Dobbs, M. B. (2013). Effects of Bracing in Adolescents with Idiopathic Scoliosis. *New England Journal of Medicine*, *369*(16), 1512–1521. https://doi.org/10.1056/NEJMoa1307337

Weinstein, S. L., Zavala, D. C., & Ponseti, I. V. (1981). Idiopathic scoliosis: Long-term follow-up and prognosis in untreated patients. *The Journal of Bone and Joint Surgery. American Volume*, *63*(5), 702–712.

Wiggins, G. C., Shaffrey, C. I., Abel, M. F., & Menezes, A. H. (2003). Pediatric spinal deformities. *Neurosurgical Focus*, *14*(1), 1–14. https://doi.org/10.3171/foc.2003.14.1.4

Wilk, B., Karol, L. A., Johnston, C. E. I., Colby, S., & Haideri, N. (2006). The Effect of Scoliosis Fusion on Spinal Motion: A Comparison of Fused and Nonfused Patients With Idiopathic Scoliosis. *Spine*, *31*(3), 309. https://doi.org/10.1097/01.brs.0000197168.11815.ec

Winter, R. B. (1997). Neurologic Safety in Spinal Deformity Surgery. *Spine*, *22*(13), 1527.

Yanik, H. S., Ketenci, I. E., Polat, A., Ulusoy, A., Deniz, G., Kose, O., & Erdem, S. (2015). Prevention of Proximal Junctional Kyphosis After Posterior Surgery of Scheuermann Kyphosis: An Operative Technique. *Clinical Spine Surgery*, *28*(2), E101. https://doi.org/10.1097/BSD.0000000000000157

Yaszay, B., Bastrom, T. P., Bartley, C. E., Parent, S., & Newton, P. O. (2017). The effects of the three-dimensional deformity of adolescent idiopathic scoliosis on pulmonary function. *European Spine Journal*, *26*(6), 1658–1664. https://doi.org/10.1007/s00586-016-4694-y

Yilmaz, G., Borkhuu, B., Dhawale, A. A., Oto, M., Littleton, A. G., Mason, D. E., Gabos, P. G., & Shah, S. A. (2012). Comparative Analysis of Hook, Hybrid, and Pedicle Screw Instrumentation in the Posterior Treatment of Adolescent Idiopathic Scoliosis. *Journal of Pediatric Orthopaedics*, *32*(5), 490. https://doi.org/10.1097/BPO.0b013e318250c629

Yoshihara, H. (2019). Surgical Treatment of Lenke Type 5 Adolescent Idiopathic Scoliosis: A Systematic Review. *Spine*, *44*(13), E788. https://doi.org/10.1097/BRS.0000000000002963

Yrjönen, T., Ylikoski, M., Schlenzka, D., & Poussa, M. (2007). Results of brace treatment of adolescent idiopathic scoliosis in boys compared with girls: A retrospective study of 102 patients treated with the Boston brace. *European Spine Journal*, *16*(3), 393–397. https://doi.org/10.1007/s00586-006-0167-z