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Reduktion der Strahlenbelastung und Optimierung der selektiven Fusion im Rahmen der operativen Therapie von Patienten mit idiopathischer Skoliose

Habilitationsschrift zur Erlangung der Venia Legendi
für das Fach Orthopädie und Unfallchirurgie
des Fachbereiches Medizin
der Heinrich-Heine-Universität Düsseldorf

vorgelegt von
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2024

Für Mama, Papa und Michael

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Inhaltsverzeichnis

Abkürzungsverzeichnis

AIS	adoleszente idiopathische Skoliose
AS	All-screws-Verfahren
BR	Bending-Aufnahmen
CT-Scans	computertomographische Scans
CSVL	central sacral vertical line
FA	Funktionsaufnahmen
HSH	Hybrid-Verfahren mit Schrauben und Haken
HSHB	Hybrid-Verfahren mit Schrauben, sublaminaren Bändern und Haken
IP	Umschlagpunkt
LIV	unterster instrumentierter Wirbelkörper
MRT	Magnetresonanztomographie
NSF	nicht selektive Fusion
PS	Pedikelschrauben
SF	selektive Fusion
WSGA	Wirbelsäulenganzaufnahme

Übersicht der beitragenden Originalarbeiten

Prost M, Windolf J, Konieczny MR. May bending radiographs be replaced by recumbent CT scans in patients with adolescent idiopathic scoliosis? Eur Spine J. **2021** Dec;30(12):3490-3497. doi: 10.1007/s00586-021-06945-7. Epub 2021 Jul 31. PMID: 34331587. [1]

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Prost M, Denz P, Windolf J, Konieczny MR. The Impact of the Lowest Instrumented Vertebra on the Correction of the Minor Curve During Selective Fusion in Patients with Adolescent Idiopathic Scoliosis. Clin Spine Surg. **2024** Sep 3. doi: 10.1097/BSD.0000000000001686. Epub ahead of print. PMID: 39226153.[4]

Prost M, Denz P, Windolf J, Konieczny MR. Impact of Different Operative Techniques for Patients with Adolescent Idiopathic Scoliosis on Frontal Curve Correction and Sagittal Balance. Int J Spine Surg. **2024** Jul 4;18(3):322-328. doi: 10.14444/8602. PMID: 38744481.[5]

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Zusammenfassung

Die idiopathische Skoliose ist ein häufiges Krankheitsbild und tritt hauptsächlich bei Kindern im Wachstumsalter auf. Abhängig vom Ausprägungsgrad der Deformität wird das Krankheitsbild operativ oder konservativ therapiert. Insbesondere die Kinder, welche operativ behandelt werden sind im Rahmen ihrer Therapie einer ausgeprägten Strahlenbelastung ausgesetzt. Durch die Fusion mehrerer Bewegungssegmente im Rahmen der operativen Therapie kommt es für die Patienten zu deutlichen Bewegungseinschränkungen, welche eindeutig mit der Patientenzufriedenheit einhergehen. Durch moderne Konzepte der selektiven Fusion kann hier ein deutlicher Beitrag zur Patientenzufriedenheit geliefert werden. In den hier präsentierten Arbeiten konnte zum einem gezeigt werden, dass routinemäßig angefertigte Schnittbildgebung zum Teil die Durchführung von präoperativen Funktionsaufnahmen obsolet machen kann, was einen erheblichen Beitrag zur Reduktion der Strahlenbelastung für die Patienten mit sich bringt. Ebenso wurde der Stellenwert der Navigation und ihr Beitrag zur sicheren Positionierung von Pedikelschrauben, sowie zur weiteren Reduktion der Strahlenbelastung für Patienten mit idiopathischer Skoliose herausgestellt.

Als Beitrag zur Verbesserung der Patientenzufriedenheit wurde die selektive Fusion mit ihrer Verkürzung der instrumentierten Strecke und der guten Adressierung des sagittalen Profils als sicheres Verfahren für ausgewählt Kurventypen bestätigt. Für den langfristigen Erfolg der selektiven Fusion ist das Erzielen einer adäquaten knöchernen Fusion essenziell, hier konnte der Einsatz von bovinen Xenografts als suffiziente Alternative für den Einsatz von Beckenkammspongiosa präsentiert werden. Für den Erfolg der selektiven Fusion ist zudem die Identifikation des untersten instrumentierten Wirbelkörpers von zentraler Bedeutung. Hier konnte gezeigt werden, dass bei der Bestimmung das sagittale Profil berücksichtigt werden sollte und sich dazu insbesondere der sagittale Umschlagpunkt hervorragend eignet.

Einleitung

Definition und Epidemiologie

Die aktuelle Leitlinie definiert die adoleszente idiopathische Skoliose (AIS) als eine dreidimensionale Wirbelsäulendeformität mit dem Beginn im Zeitraum zwischen 10 und 18 Jahren und ohne klar erkennbare Ursache, d.h. unabhängig von anderen Krankheiten. [7] Die Prävalenz der AIS beträgt bis zu 5,2%. Leichte Skoliosen treten bei Jungen und Mädchen annähernd gleich häufig auf, wobei die Prävalenz von Skoliosen mit höherem Cobb-Winkel bei Mädchen deutlich stärker ansteigt als bei Jungen. [8]

Einteilung und Therapiekonzepte

Elementarer Baustein der Diagnostik der Erkrankung ist bei auffälliger klinischer Untersuchung die radiologische Diagnostik mittels Wirbelsäulenganzaufnahme (WSGA) in 2 Ebenen im Stand. Anhand dieser Röntgenbilder kann zur Quantifizierung des Ausmaßes der Skoliose die Bestimmung des Cobb-Winkels erfolgen.[7,9,10]

Basierend auf den WSGA im Stand und zusätzlich durchgeführten Bending-Aufnahmen (BR) zur Beurteilung, ob einzelne Nebenkurven struktureller oder nicht-struktureller Natur sind, erfolgt die Einteilung der Skoliosen nach Lenke. [11] Diese Klassifikation stellt aktuell die gängigste Klassifikation dar. Sie weist eine verlässliche Planung der operativen Therapie auf und hat zudem eine hohe intra- und interobserver Verlässlichkeit. [12,13]

Die Therapiekonzepte richten sich nach dem unterschiedlichen Schweregrad der AIS gemessen am Cobb-Winkel. So wird bei jedem Patienten mit diagnostizierter AIS regelhafte skoliosespezifische Physiotherapie und Eigenübungen empfohlen. Am häufigsten werden die physiotherapeutischen Konzepte nach Katharina Schroth empfohlen. Insgesamt ist die Studienlage bezüglich des Nutzens der Physiotherapie sehr heterogen und es liegt wenig Evidenz vor. [7,14–17] Weiterhin wird bei noch nicht stattgehabten Wachstumsabschluss und gemessenen Cobb-Winkeln der Hauptkrümmung ab 25° thorakal bzw. ab 20° thorakolumbal oder lumbal eine zusätzliche Korsetttherapie empfohlen.[7,18–20]

Ziel der Korsetttherapie ist langfristig eine Verschlechterung des Ausgangsbefundes zu verhindern. Dauerhafte Korrekturen des Cobb-Winkels, besser als im Vergleich zu dem zu Beginn der Behandlung gemessenen Cobb-Winkel, können nur selten erreicht werden.[21] Um dieses Therapieziel zu erreichen, sollte nach Korsettanpassung eine Korrektur des Cobb-

Winkels im Korsett um ca. 40% erreicht werden.[7,22] Die besten Ergebnisse können durch die Korsetttherapie erzielt werden, wenn eine Tragedauer von mindestens 18 Stunden pro Tag erreicht wird.[23–26] Bezüglich des zu wählenden Korsett-Typs besteht noch keine eindeutige Datenlage. Die vorhandenen Daten zeigen am ehesten, dass mit rigiden Orthesen, wie zum Beispiel einem Cheneau-Korsett die besten Korrekturen erreicht werden können. [27,28] Um ein Rezidiv im Progress der Deformität zu verhindert sollte die Korsetttherapie bis zum Wachstumsabschluss fortgeführt werden.[29] Grundsätzlich sollten alle Patienten mit AIS während ihres Wachstums klinisch und bei Bedarf auch radiologisch alle 4-6 Monate kontrolliert werden.[7]

Laut aktueller Leitlinie sollte bei AIS-Patienten mit verbleibendem Restwachstum oder nach Abschluss des Wachstums und Cobb-Winkeln der Hauptkrümmung > 50° thorakal bzw. > 40° thorakolumbal oder lumbal die Indikation zur operativen Korrektur der Skoliose gestellt werden. Zwischen 40° und 50° Cobb-Winkel thorakal kann eine OP erwogen werden.[7] Bei der Entscheidung für oder gegen eine OP ist auch das sagittale Profil wichtig und muss Berücksichtigung finden. Begründet sind diese Grenzwerte in dem Wissen, dass Hauptkrümmung > 50° thorakal bzw. > 40° thorakolumbal oder lumbal in den meisten Fällen auch nach Wachstumsabschluss einen weiteren Progress aufweisen. Es wird ein durchschnittliches Voranschreiten um ca. 1° pro Jahr beschrieben.[30–32] Weiter fortschreitende Deformitäten führen im Verlauf auch zu zunehmenden Einschränkungen für die betroffenen Patienten. Hier werden neben Schmerzen und Bewegungseinschränkungen auch deutliche psychische Probleme, insbesondere bedingt durch die optische Deformierung, beschrieben. Ebenso sind im Verlauf auftretende kardiale und insbesondere restriktive pulmonale Einschränkungen, welche zur signifikanten Reduktion der Lebensqualität führen können, nachweisbar. [32–36]

Präoperative bildgebende Diagnostik

Funktionsaufnahmen

Basierend auf den aktuellen Leitlinienempfehlungen sollten nach Indikationsstellung zur operativen Therapie Funktionsaufnahmen (FA) in beide Richtungen oder Aufnahmen unter Traktion durchgeführt werden. Diese dienen dazu die Flexibilität der Deformität zu bewerten.[7] In der Literatur wird eine Vielzahl an verschiedenen FA bzw. BR beschrieben. [37] Die Studienlage bezüglich der Aussagekraft und der jeweils durch die verschiedenen Aufnahmen erfassten

Parameter ist sehr heterogen, sodass letztendlich keine einheitliche Meinung dazu besteht, welche Art von FA präoperativ angefertigt werden sollte. [7,38]

Zu denen am häufigsten durchgeführten Aufnahmen zählen unter anderem die BR. Diese Aufnahmen können im Stehen oder in Rückenlage angefertigt werden. Dabei führt der Patient eine maximale aktive Seitneigung, jeweils nach rechts und nach links durch. Diese Art der FA ist besonders gut geeignet zur Beurteilung der Flexibilität von thorakolumbalen und hochthorakalen Krümmungen. Weiterhin dienen diese Aufnahmen der Planung des untersten instrumentieren Wirbelkörpers (LIV). Hierfür wird die Horizontalisierung der einzelnen Wirbelkörper beurteilt. [39]

Ebenso gängig sind die Hypomochlion- oder auch Fulcrum-Aufnahmen, welche in Seitenlage angefertigt werden. Unter dem Scheitelbereich der jeweiligen zu analysierenden Krümmung wird auf die Konvexseite ein Polster als Wiederlager untergelegt. Im Vergleich zu den BR können diese Aufnahmen insbesondere bei milderen Krümmungen die Flexibilität der jeweiligen Krümmung besser darstellen. Diese Aussagekraft ist für die thorakalen Hauptkrümmungen am validesten. [37,39,40] Ebenso kann durch diese Art an FA das erreichbare postoperative Korrekturergebnis am genauesten vorausgesagt werden.[41,42]

Den Effekt der Korrektur der Hauptkrümmung auf die Nebenkrümmung können am besten push-prone-Aufnahmen nachweisen. Hierfür wird, in Rücken- oder Bauchlage nach einem 3-Punkte-Prinzip, die Wirbelsäule an Axilla und Becken stabilisiert und mit Hilfe von Polstern oder der Hand Druck auf die Wirbelsäule im Scheitelbereich von konvexseitig ausgeübt. In dieser Position wird dann eine WSGA angefertigt. [39]

Die Einstellung des koronaren Lotes kann man am besten im Rahmen von Extensionsaufnahmen beurteilen. Diese Art der FA kann jedoch auch die Flexibilität der Haupt- und Nebenkurven darstellen. Insbesondere bei stark ausgeprägten Krümmungen haben diese Aufnahmen die beste Aussagekraft. [37] Sie können im Stehen, in Bauch- oder Rückenlage sowie unter Ausübung eines zusätzlichen manuellen Drucks erfolgen. Es gibt technische Vorrichtungen zur Durchführung dieser Aufnahmen (Cotrel-Extension) oder sie werden unter manueller Extension durchgeführt. [43]

Schnittbilddiagnostik

Eine präoperative Schnittbildgebung mittels Magnetresonanztomographie (MRT) der gesamten Wirbelsäule wird in der aktuellen Leitlinie eindeutig empfohlen. Computertomographischen Scans (CT-Scans) werden nicht als präoperative Routine-

Diagnostik einer AIS angesehen. Sie können aber bei klarer Fragestellung dennoch ihre Indikation haben. [7]

Grundlage für die Empfehlung zum präoperativen MRT ist es etwaige intraspinale Fehlbildungen, wie eine Syringomyelie, eine Arnold-Chiari-Malformation oder ein Tethered-Cord, präoperativ aufzudecken.

Die Inzidenz von intraspinalen Fehlbildungen liegt bei bis zu 9,5%.[44–47] Eine unauffällige Anamnese und ein klinisch unauffälliger Reflexstatus sowie normale Bauchhautreflexe allein reichen nicht aus, um solche intraspinalen Pathologien sicher auszuschließen. International werden diese Empfehlungen jedoch bisher nur eingeschränkt umgesetzt. In einer internationalen Expertenbefragung fanden jedoch nur 54% der Befragten eine präoperative MRT für notwendig. [38]

Notwendige Voraussetzung für die Durchführung eines präoperativen CT-Scans der Wirbelsäule bei Patienten mit AIS sind exakt formulierte klinische Informationen und Fragestellung und die damit begründbare rechtfertigende Indikation. CT-Scans dienen insbesondere der Darstellung der knöchernen Strukturen, der Weite des Spinalkanals sowie der Implantatlage. Gerechtfertigt sein kann ein CT-Scan insbesondere bei voroperierten Patienten sowie bei ausgeprägten Krümmungen zur Beurteilung der knöchernen Anatomie, z.B. von knöchernen Überbrückungen einzelner Segmente und Planung der Instrumentation. Im Fall einer geplanten intraoperativen Navigation kann diese auf Basis einer präoperativen CT durchgeführt werden und somit eine solche im Vorfeld rechtfertigen.[7]

Strahlenbelastung

Die Strahlenbelastung welcher Patienten mit AIS während ihrer Behandlung bedingt durch die aktuell als Standard angesehenen Untersuchungen ausgesetzt sind ist immens. Diesbezüglich sind die operativ behandelten Patienten besonders zu beachten. Diese haben eine mehr als 10-mal höhere Strahlendosis als im Korsett behandelte oder konservativ verlaufsbeobachtete Patienten. Der Großteil der Strahlendosis entfällt dabei auf die perioperative Bestrahlung. [48]

Die Folgen der Strahlenbelastung für die Patienten sind erheblich. In einem aktuellen Review zeigte sich eine, im Vergleich zur Allgemeinbevölkerung, erhöhte Rate an Mamma-Karzinomen und eine erhöhte Tumorsterblichkeit. [49] Weiterhin konnte in einer genetischen Grundlagen-Arbeit gezeigt werden, dass bei AIS-Patienten im Vergleich zu Kontrollpatienten signifikant häufiger röntgenstrahlenbedingte Schäden an der DNA vorliegen. [50]

Auch die aktuelle Leitlinie weist explizit auf diese erhöhte Strahlenbelastung hin und mahnt dazu mögliche Maßnahmen zur Reduktion der Strahlenbelastung für die Patienten zu prüfen und zu Ergreifen. [7]

Operative Techniken und Strategien

Vergleich der ventralen und dorsalen Spondylodese

Als Ankerpunkte im Rahmen der Spondylodese von dorsal dienen Pedikelschrauben oder Haken und Bänder. Die beiden letzteres werden an den dorsalen Strukturen, insbesondere den Laminae oder Querfortsätzen, angebracht. Von ventral können Wirbelkörperschrauben über eine Thorakotomie oder Lumbotomie direkt in die Wirbelkörper eingebracht werden.
Sowohl mit ventralen als auch mit dorsalen Operationsverfahren können gute Ergebnisse in Hinblick auf Korrektur, Funktion und Patientenzufriedenheit erzielt werden.[7]
Vorteil der ventralen Technik ist, dass hier einfach die Bandscheiben im Instrumentationsbereich reseziert werden können. Dies führt zu einem relevanten Release, was zu einer besseren Derotation beiträgt. Bei den dorsalen Verfahren muss diese Korrektur über die Implantate gegen den Widerstand der in situ verbleibenden Bandscheiben durchgeführt werden. [51] Neuere Forschungsergebnisse zeigen jedoch, dass durch die moderneren dorsalen Fusionssysteme ebenfalls eine adäquate und gute Derotation erzielt werden kann.[52]
Ein weiterer Vorteil, welcher den ventralen Fusionsverfahren zugeschrieben wird ist der, dass bei diesen Verfahren in der Regel eine Instrumentation bis zum kaudalen Endwirbel einer Krümmung ausreichend ist. [53,54] Bei der dorsalen Fusion ist meist eine Fusionsstrecke, in der Regel bis zum kaudalen Neutralwirbel oder bis zu dem stabilen Wirbel, der von der central sacral vertical line (CSVL) mittig geschnitten wird, notwendig. [55,56] Letzteres führt dazu, dass bei dorsalen Korrekturspondylodesen häufig etwas länger nach kaudal instrumentiert wird als bei ventralen Korrekturspondylodesen. Somit können bei der ventralen OP häufig einige kaudale Bewegungssegment eingespart werden, was in einer kürzeren Fusionsstrecke und einer besseren postoperativen Restbeweglichkeit mündet.
Im Rahmen der modernen Konzepte der selektiven Fusion (SF) wird insbesondere unter Einbeziehung der FA auch bei Fusionen von dorsal zunehmend kürzer instrumentiert.[55–58]
Somit ist keine allgemeingültige Aussage darüber möglich, ob eine dorsale Spondylodese per se immer länger sein muss als eine ventrale.

Diese kürzere Fusionsstrecke im Rahmen der selektiven Fusion ist ein zentraler Faktor, welcher die postoperative Zufriedenheit der Patienten mit am meisten beeinflusst. Luo et al verglichen Patienten, bei welchen eine SF durchgeführt wurde mit Patienten, welche herkömmlich langstreckig fusioniert wurden. Sie konnten zeigen, dass die SF mit weniger Schmerzen und signifikant höheren Werten in gängigen Scores zur Patientenzufriedenheit einhergeht [59]. Weitere Untersuchungen konnten zeigen, dass die Länge der Fusionsstrecke unter anderem von elementarer Bedeutung bezüglich der Möglichkeit zur Rückkehr zum Sport ist [60]. Auch konnte gezeigt werden, dass längere Fusionsstrecken bei Frauen die Wahrscheinlichkeit zur Notwendigkeit eines Kaiserschnittes erhöhen [61].

Einen eindeutigen Vorteil, den die dorsale Korrekturspondylodese gegenüber der ventralen Spondylodese hat ist der, dass nahezu alle Krümmungen von dorsal adressierbar sind. Bei der ventralen Korrekturspondylodese können in einer Sitzung nur einbogige Krümmungen adressiert werden (Lenke Typ 1 oder Typ 5). Der kranialste von ventral zu erreichende Wirbelkörper ist ca. BWK 5. [62] Als weiterer Nachteil der ventrale Korrekturspondylodese ist zu benennen, dass bei ventralen thorakalen Verfahren ein erhöhtes Risiko für eine intra- oder postoperative Verschlechterung der Lungenfunktion besteht, insbesondere wenn diese bereits präoperativ eingeschränkt ist. [63,64]

Vergleich der dorsalen Spondylodeseverfahren

Pedikelschrauben sind der Standard bei der dorsalen Korrekturspondylodese und den reinen Hakensystemen überlegen. Sublaminäre Bänder haben ein ähnliches koronares Korrekturpotential wie Pedikelschrauben. Es gibt eine Vielzahl von Kombinationsmöglichkeiten der verschiedenen Verankerungssysteme in Rahmen von Hybridversorgungen.

Bezüglich der Implantatdichte zeigt die aktuelle Literatur, dass eine höhere Implantatdichte in der Regel mit einer besseren Korrektur der Hauptkrümmung einher geht. [65] Ob dieser zusätzliche Korrekturgewinn mit einer gesteigerten Patientenzufriedenheit einhergeht, bleibt jedoch unklar.[66]

Für „All-screws“-Verfahren (AS) wird durch Clement et al. eine durchschnittliche Korrektur von bis zu 64% in der koronaren Ebene beschrieben, welche bei einer Implantatdichte von 100% sogar bis zu 78% gesteigert werden kann. Mit Haken-Systemen wird lediglich eine Korrektur von bis zu 55% beschrieben. Jedoch scheint durch die Haken-Systeme eine bessere Wiederherstellung der Kyphose im Rahmen der sagittalen Balance möglich zu sein. [65]

Die Verwendung von zusätzlichen sublaminären Bändern im Rahmen der operativen Therapie der AIS wurde von Mazda et al. erstmals beschrieben. Er baute einen Rahmen aus zwei Stäben, die er mit Querverbindern verband und befestigte ihn lumbal an Pedikelschrauben und proximal an Haken. Dann führte er eine Translation der BWS zum Stab aus. Thorakal korrigierte er so die Skoliose um 63%. Die Kyphose nahm bei dieser Prozedur um 9° zu. [67]
Durch die Kombination aus lumbalen Schrauben und thorakalen Pedikelhaken kann durchschnittlichen eine Korrektur von bis zu 60% im koronaren Profil erreicht werden. Dieser scheint das Vorgehen mit lumbalen Schrauben und thorakalen sublaminaren Bändern mit einer Korrektur von bis zu 75% im koronaren Profil und besserer Korrektur des sagittalen Profils überlegen zu sein. [68] Insbesondere scheint durch die Verwendung von sublaminaren Bändern im Vergleich zu den anderen Verankerungsmöglichkeiten eine deutlich verbesserte Korrektur der thorakalen Kyphose möglich zu sein. [69,70]
Die Stabeigenschaften (Steifigkeit, Durchmesser und Material) haben einen Einfluss auf die coronare und vor allem auf die sagittale Korrektur. All diese Eigenschaften treten jedoch in Kombination mit anderen Faktoren wie Verankerungsmethode, Implantatdichte und Krümmungseigenschaften auf. Von zentraler Bedeutung ist hier, dass der passende Stab für die gewählte Verankerungsmethode, das geplante Repositionsmanöver und die jeweiligen Krümmungseigenschaften der Deformität gewählt wird. [71–74]
Bezüglich der Frage nach der Implantationstechnik für die Pedikelschrauben besteht weiterhin keine einheitliche Empfehlung. Zur Verfügung stehen neben der klassischen Freihandtechnik sowie der Bildwandler gestützten Technik mittlerweile eine Vielzahl von Navigation gestützten oder Roboter gestützten Techniken. Die Bandbreite der Studienergebnisse in Bezug auf Rate an Schraubenfehllagen und Strahlenbelastung der verschiedenen Techniken ist immens und lässt keine einheitliche Bewertung zu. In einem aktuellen Review bezüglich dieser Thematik von Ansorge et al. aus 2023 wird jedoch eine klare Empfehlung zum Nutzen der Navigation bzw. der Robotik für komplexe Deformitäten oder Revisionseingriffe ausgesprochen. [75]
Um eine sichere und langfristige knöcherne Fusion zu erreichen ist neben einer dorsalen Dekortikation die Anlage von autologer Spongiosa indiziert. Da insbesondere bei langen Fusionsstrecken, wie bei der operativen Therapie der AIS die lokal, z.B. im Rahmen der durchgeführten Osteotomien gewinnbare Spongiosa häufig nicht ausreichend ist, war es lange Zeit Goldstandard zusätzlich Beckenkammspongiosa anzulagern. [76–78] Da dieses Verfahren

jedoch mit einer deutlichen Entnahmemorbidität einhergeht werden heutzutage meist Knochenersatzmaterialien additiv verwendet. [78–82]

Bestimmung der notwendigen Fusionsstrecke im Rahmen der selektiven Fusion

Das unter anderem von Lenke et al. propagierte und heutzutage bei entsprechender Deformität regelhaft durchgeführte Konzept der SF basiert darauf, dass sich die Fusionsstrecke auf die strukturelle Hauptkurve beschränkt und sich die nicht instrumentierten nicht-strukturellen Nebenkurven passiv mit korrigieren. [11,83–85]

Elementar für den Erfolg dieses Verfahrens ist die adäquate Auswahl des LIV. [55] Die Festlegung des optimalen LIV erfolgt unter anderem anhand der präoperativen Bildgebung. Welche radiologischen Parameter sich jedoch am besten zur Festlegung des LIV, insbesondere bei thorakalen Kurven eignen ist weiterhin nicht abschließend geklärt. Lange Zeit galt der Wirbelkörper, welcher mittig von der CSVL getroffen wird als Marker zur Festlegung des LIV. [55,56] Im weiteren Verlauf wurde dann der letzte Wirbelkörper, welcher noch von der CVSL berührt wird als möglicherweise optimaler LIV beschrieben. Die geringere Fusionsstrecke hier geht jedoch mit einer gering erhöhten Rate an sekundärem Progress der Deformität einher. Dies konnte insbesondere bei noch deutlicher Wachstumsreserve beobachtet werden, zeigte sich letztendlich jedoch klinisch nicht relevant.[57,58] Wang et al. empfehlen weiterhin den Wirbelkörper als LIV zu wählen, welcher als erster Wirbelkörper kranial des Sakrums einen Abstand von mehr als 10 mm von der CVSL aufweist. Hier beobachteten Sie in ihrem Patientenkollektiv das beste Verhältnis zwischen Risiko eines sekundären Progresses der Deformität und lumbaler Restbeweglichkeit. [86] Dubousset beschreibt den kranialsten Wirbelkörper, welcher folgende Eigenschaften aufweist als optimalen LIV: Neutralität in Form von parallelen Pedikeln im frontalen Röntgenbild; Lage innerhalb einer Zone zwischen zwei parallelen vertikalen Linien ausgehend von den lumbosakralen Facettgelenken; Lage unmittelbar oberhalb der Bandscheibe, welche sich im Rahmen der Bending-Aufnahmen als Flexibel zeigt; Segmentale Kyphose im lateralen Röntgenbild unter 10°. [87] Sun et al. schreiben dem Endwirbel der Deformität zentrale Bedeutung in der Wahl des LIV zu. Sie differenzieren zudem noch abhängig von der Schwere der Deformität. Für Deformitäten mit einem Cobb-Winkel kleiner 60° empfehlen Sie den Endwirbel als LIV zu wählen, für Deformitäten über 60° hingegen empfehlen sie einen Wirbelkörper distal des Endwirbels als LIV zu wählen.[88]

Rizkallah et al. verglichen verschiedene Verfahren zur Auswahl des LIV miteinander um kamen zum Schluss, dass die Übereinstimmung der basierend auf den gewählten Verfahren identifizierten LIV´s nur moderat ist. Sie empfehlen am ehesten mehrere Verfahren zu kombinieren, der Wirbelkörper mit den meisten Übereinstimmungen aus verschiedenen Verfahren beschreiben sie als besten LIV. Von den Einzelverfahren zur Bestimmung des LIV sehen sie die meisten Vorteile bei dem Verfahren nach Dubousset.[87]

Fischer et al. untersuchten die größten Risikofaktoren für einen sekundären Progress der Deformität. Sie beschrieben hier die Wahl eines LIV, welcher nicht in Kontakt mit CSVL steht oder eines LIV 3 oder mehr Level kranial des neutralen Wirbelkörpers, als größte Risikofaktoren. Weiterhin sahen sie insgesamt ein höheres Risiko des sekundären Progresses der Deformität bei noch deutlicher Wachstumsreserve und dem Vorliegen eines lumbalen Modifiers Typ C nach Lenke. [55]

Eigene Studien und Ergebnisse

Ziel der eigenen Studien war es zum einen Maßnahmen zur Reduktion der Strahlenbelastung von Patienten mit idiopathischer Skoliose zu etablieren. Hierfür wurde zum einen geprüft, ob die präoperative Schnittbildgebung Teile der strahlenintensiven nativen Röntgendiagnostik ersetzten kann und weiterhin wurde der Nutzen der Navigation in Bezug auf die Reduktion der Strahlenbelastung geprüft. Als zweites Ziel wurden Strategien zur Optimierung der selektiven Fusion geprüft. Hierzu wurde zum einen ein neuer Parameter der Bestimmung des LIV identifiziert, die zu Verfügung stehenden Verankerungsmöglichkeiten analysiert und der sichere Einsatz von bovinen Xenografts zum Erzielen der knöchernen Fusion bestätigt.

1. Können präoperative Bending-Aufnahmen bei Patienten mit idiopathischer Skoliose durch ein CT im Liegen ersetzt werden?

Prost M, Windolf J, Konieczny MR. May bending radiographs be replaced by recumbent CT scans in patients with adolescent idiopathic scoliosis? Eur Spine J. **2021**

Im Rahmen der modernen Konzepte der SF im Rahmen der operativen Therapie von Patienten mit AIS haben präoperative BR aktuell einen elementaren Stellenwert. Sie dienen der Klassifikation von Nebenkurven als Strukturell und Nicht-Strukturell.[11,83,84] Es gibt eine Vielzahl an verschiedenen Techniken zur Durchführung von BR. Alle haben gemeinsam, dass sie mit zusätzlicher Strahlenbelastung für den Patienten und teilweise auch dem Personal einhergehen.[89–93] Heutzutage werden präoperativ häufig CT-Scans durchgeführt, um entweder die Operation detaillierter zu planen oder als Grundlage für die Navigation dienen. Ziel dieser Studie war es zu untersuchen, ob diese CT-Scans die präoperativen BR ersetzen können.

Hierfür wurden retrospektiv die Bilddaten von 39 Patienten, welche präoperativ in unserer Klinik sowohl ein CT-Scan als auch BR erhalten haben analysiert. In den nativen präoperativen Röntgenbildern, den präoperativen BR sowie den präoperativen CT-Scans wurden sämtliche Cobb-Winkel der Haupt- und Nebenkurven miteinander bestimmt und miteinander verglichen. Siehe dazu beispielhaft ***Abbildung 1***.

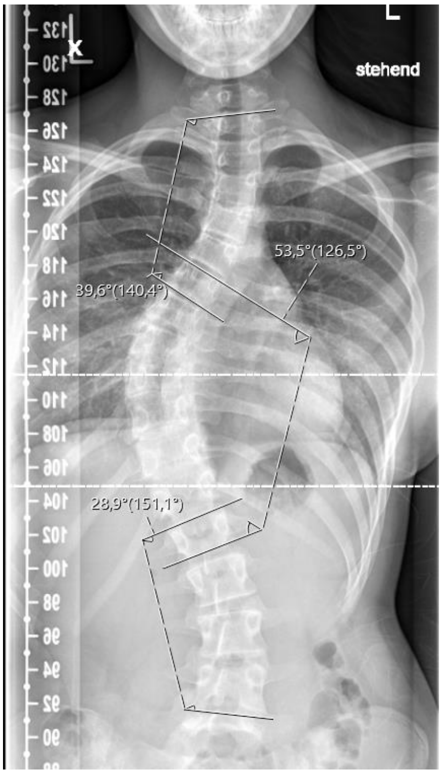
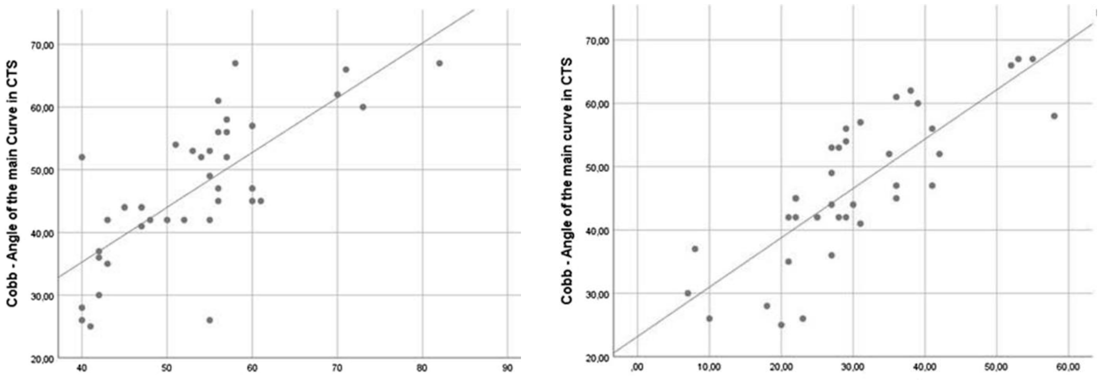


Abbildung 1 Messung der Cobb-Winkel
Messung der Cobb-Winkel von Haupt-, sowie kranialer und kaudaler Nebenkurve in einer Wirbelsäulenganzaufnahme a.p. im Stand. Mit freundlicher Genehmigung durch Univ.-Prof. Dr. G. Antoch, Institut für diagnostische und interventionelle Radiologie.

Die statistische Auswertung ergab eine signifikante Korrelation der Messwerte für die Cobb-Winkel der Haupt- bzw. der Nebenkurven sowohl zwischen den WSGA im Stand und den CT-Scans ($r=0.746$, $p < 0.01$ bzw. $r=0.671$, $p < 0.01$) als auch für die Cobb-Winkel der Haupt- bzw. der Nebenkurven zwischen den BR und den CT-Scans ($r=0.806$, $p < 0.01$ bzw. $r=0.601$, $p < 0.01$). Die Korrelationen werden beispielhaft in ***Abbildung 2*** gezeigt.



A **B**

Abbildung 2. Korrelationsanalyse zwischen den verschiedenen Cobb-Winkeln
Korrelation zwischen dem Cobb-Winkel der Hauptkurve im CT-Scan (CTS), sowie der Wirbelsäulenganzaufnahme (FSR) (Bild A) bzw. den Bending-Aufnahmen (PPR) (Bild B). Auf der X-Achse ist der Cobb-Winkel der Hauptkurve im FSR (Bild A) bzw. der Hauptkurve im PPR (Bild B) und auf der Y-Achse der Cobb-Winkel der Hauptkurve im CTS dargestellt. Mit freundlicher Genehmigung von Springer Nature im Rahmen der Open Acess Veröffentlichung unter Creative Commons Lizenz.

Weiterhin wurden im Rahmen einer Subgruppenanalyse alle Patienten mit einer Nebenkurve von kleiner 40° in der WSGA betrachtet. Hier zeigte sich, dass diese Patienten immer, wenn sie einen Cobb-Winkel von kleiner 25° in den BR hatten (Definition für nicht-strukturelle Kurven) einen Cobb-Winkel im CT-Scan von kleiner 35° hatten.
Zusammenfassend konnte in dieser Studie gezeigt werden, dass die Messung der Cobb-Winkel im CT-Scan signifikant mit den Messungen der Winkel in der anderen Bildgebung korrelieren und das Kurven im CT-Scan mit einem Cobb-Winkel von kleiner 35° als nicht
-strukturell definierbar sind und in Bezug auf diese Fragestellung ein präoperativer CT-Scan die präoperativen BR ersetzen kann. Einen Beitrag zum Strahlenschutz für den Patienten hat dieses Ergebnis, sofern ein CT im Rahmen der präoperativen Planung notwendig ist.

2. Können präoperative Bending-Aufnahmen bei Patienten mit idiopathischer Skoliose durch ein MRT im Liegen ersetzt werden?

Prost M, Röckner ME, Taday R, Windolf J, Konieczny MR. May bending radiographs be replaced by magnetic resonance imaging in patients with adolescent idiopathic scoliosis? Eur Spine J. **2023**

Die aktuell gängige Leitlinie zur Therapie von AIS empfiehlt eine präoperative MRT der gesamten Wirbelsäule zur OP-Planung.[7] Ebenso ist bekannt, dass Patienten während ihrer Behandlung für die AIS einer immensen Strahlenbelastung mit messbaren Folgeschäden ausgesetzt sind.[94,95] Basierend auf dieser Empfehlung, den Langzeitfolgen der Strahlenbelastung und basierend auf den Ergebnissen der Vorläuferstudie zur Untersuchung, ob BR durch präoperative CT-Scans ersetzt werden können,[1] führten wir diese Studie durch um zu eruieren, ob auch ein präoperatives MRT die präoperativen Bending-Aufnahmen ersetzten kann.
Anlaog zum Protokoll der Vorläuferstudie wurden auch hier retrospektiv die Bilddaten von 25 Patienten, welche präoperativ in unserer Klinik sowohl ein MRT als auch BR erhalten haben analysiert. In den nativen präoperativen Röntgenbildern, den präoperativen BR sowie den präoperativen MRT-Scans wurden sämtliche Cobb-Winkel der Haupt- und Nebenkurven miteinander bestimmt und miteinander verglichen. Siehe dazu beispielhaft ***Abbildung 3.***

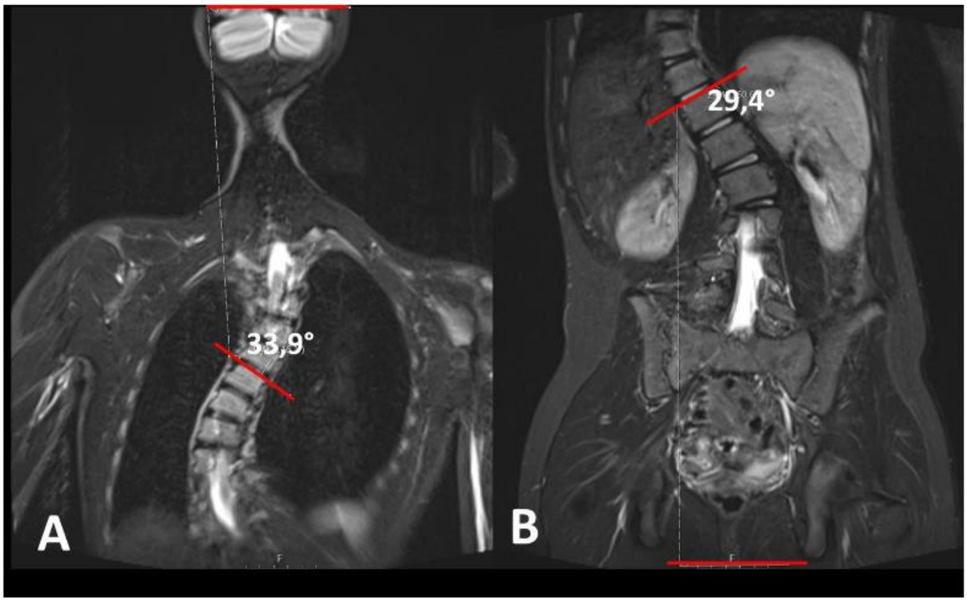


Abbildung 3 Messung des Cobb-Winkels der Hauptkurve in einem MRT Schnitt
Bild A koronare Rekonstruktion eines kranialen Abschnittes eines MRT´s der Wirbelsäule (T2 gewichtet). Es wird der kraniale Endwirbel der Kurve bestimmt und der Winkel zwischen seiner Deckplatte und der Horizontalen gemessen (hier 33,9°). Bild B koronare Rekonstruktion eines kaudalen Abschnittes eines MRT´s der Wirbelsäule (T2 gewichtet). Es wird der kaudale Endwirbel der Kurve bestimmt und der Winkel zwischen seiner Grundplatte und der Horizontalen gemessen (hier 29,4°). Die Summe der in A und B gemessenen Winkel ergibt den Cobb-Winkel der jeweiligen Kurve (hier 63,3°). Mit freundlicher Genehmigung durch Univ.-Prof. Dr. G. Antoch, Institut für diagnostische und interventionelle Radiologie.

Die statistische Auswertung der Messwerte zeigte erneut eine signifikante Korrelation zwischen der Messwerte für die Cobb-Winkel der Haupt- bzw. der Nebenkurven sowohl zwischen den WSGA im Stand und den MRT-Scans ($p < 0.05$, CorrCoeff=0.41 bzw. $p < 0.05$, CorrCoeff=0.47) als auch für die Cobb-Winkel der Haupt- bzw. der Nebenkurven zwischen den BR und den MRT-Scans ($p < 0.05$, CorrCoeff=0.41 bzw. $p < 0.001$, CorrCoeff=0.9). Ebenso wurden erneut im Rahmen einer Subgruppenanalyse alle Patienten mit einer Nebenkurve von kleiner 40° in der WSGA betrachtet. Hier zeigte sich, dass diese Patienten immer, wenn sie einen Cobb-Winkel von kleiner 25° in den BR hatten (Definition für nicht-strukturelle Kurven) einen Cobb-Winkel im MRT von kleiner 30° aufwiesen.

Zusammenfassend konnte in dieser Studie gezeigt werden, dass auch die Messung der Cobb-Winkel im MRT mit den Messungen der Winkel in der anderen Bildgebung korrelieren und das Nebenkurven im MRT mit einem Cobb-Winkel von kleiner 30° als nicht-strukturell definierbar sind und in Bezug auf diese Fragestellung das präoperative MRT die präoperativen BR ersetzen kann. Hierdurch konnte durch die Erweiterung der Aussagekraft eines präoperativen MRTs, ein Beitrag zur Reduktion der Strahlenbelastung für die Patienten erzielt werden.

3. Effektive Strahlendosis pro Schraube in der operativen Therapie von Skoliosen. Matched-Pair Analyse von 293 in 3 verschiedenen Techniken implantierten Pedikelschrauben

Konieczny MR, Boos J, Steuwe A, Schleich C, **Prost M**, Krauspe R. Effective dose of radiation per screw in surgery of adolescent idiopathic scoliosis: matched pair analysis of 293 pedicle screws inserted using three different techniques. J Child Orthop. **2020**.

Der Einsatz von Navigationsverfahren zum Einbringen von Pedikelschrauben (PS) weist in den vorliegenden Studien eine deutlich reduzierte Anzahl an Schraubenfehllagen im Vergleich zur klassischen bildwandlergestützten Technik auf. Insbesondere im Bereich der thorakalen Wirbelsäule wird eine 5-fach höhere Präzision der Schraubenlage beschrieben.[96–99] Ebenso gibt es klare Daten, die zeigen, dass es durch die Navigation zu einer signifikanten Reduktion der Strahlenbelastung für das OP-Team kommt. [100–102] Uneinheitliche Aussagen gibt es jedoch in Bezug auf den Einfluss des Einsatzes der Navigation bei der Implantation von PS auf die Strahlenbelastung des Patienten. [102–106]

Um dieser Fragestellung nachzugehen, wurden in dieser Studie im Rahmen einer matched-pair Analyse Patienten eingeschlossen, die in unserer Abteilung mittels dorsaler Korrekturspondylodese bei AIS versorgt wurden. Es wurden Subgruppen gebildet (PS-Implantation mittels Bildwandler, PS-Implantation mittels Navigation und präoperativen CT-Scan sowie PS-Implantation mittels Navigation und intraoperativem 3D-Scan) und die Strahlenbelastung pro implantierte Schraube in der jeweiligen Technik bestimmt. Insgesamt wurden 293 Schrauben implantiert.

Im Rahmen der statistischen Auswertung konnte gezeigt werden, dass die Implantation von PS gestützt auf eine Navigation mit intraoperativem 3D-Scan, sowohl gegenüber der Navigation mit präoperativen CT-Scan (0.025 mSv vs. 1.0 mSv; $p < 0.0001$) als auch gegenüber dem klassischen Bildwandler gestützten Verfahren (0.025 mSv vs. 0.781 mSv; $p < 0.001$) mit einer signifikanten Reduktion der Strahlendosis pro implantierter PS einhergeht, welcher der Patient ausgesetzt ist. Auch ist bei der Implantation von PS gestützt auf eine Navigation mit intraoperativem 3D-Scan die intraoperative Strahlungsdauer im Vergleich zur klassischen bildwandlergestützten Verfahren signifikant verringert (13,5 sec pro PS vs. 24,1 sec pro PS; $p < 0.0001$). Zu klinisch relevanten Schraubenfehllagen kam es lediglich im Rahmen der klassischen bildwandlergestützten Technik.

Zusammenfassend konnte in dieser Studie gezeigt werden, dass die Implantation von PS gestützt auf die Navigation mit intraoperativen 3D-Scan bei Patienten mit AIS ein sicheres

Verfahren ist, was zur signifikanten Reduktion der Strahlenbelastung für die Patienten führt. Dieses Verfahren ist seit dieser Studie Standard in unserer Klinik geworden.

4. Einfluss verschiedener OP-Techniken auf die Korrektur der frontalen Kurve sowie der sagittalen Balance bei Patienten mit idiopathischer Skoliose

Prost M, Denz P, Windolf J, Konieczny MR. Impact of Different Operative Techniques for Patients with Adolescent Idiopathic Scoliosis on Frontal Curve Correction and Sagittal Balance. Int J Spine Surg. **2024**

Nach Indikationsstellung zur operativen Therapie bei AIS kann diese mittels einer Vielzahl von möglichen Techniken ausgeführt werden. Aktueller Standard hierfür ist die Korrekturspondylodese, welche von ventral oder häufiger von dorsal durchgeführt werden kann. [7] Bei der dorsalen Korrekturspondylodese kann wiederrum, basierend auf den verwendeten Implantaten, zwischen AS-Verfahren, Hybrid-Verfahren mit Schrauben und Haken (HSH) sowie Hybrid-Verfahren mit Schrauben, sublaminaren Bändern und Haken unterscheiden werden (HSHB).[107–111] Weiterhin muss basierend auf der Länge der fusionierten Strecke zwischen einer SF, bei welcher nur die strukturelle Hauptkurve adressiert wird und einer nicht-selektiven Fusion (NSF), bei welcher auch nicht-strukturelle Nebenkurven adressiert werden, unterschieden werden.[83,84,85,112,113] Ziel dieser Arbeit war den Einfluss dieser verschiedenen Techniken auf das zu erreichende Korrekturpotential der Haupt- und Nebenkurve im frontalen Profil sowie auf das sagittale Profil der Patienten zu analysieren.
Hierfür führten wir eine retrospektive Datenanalyse durch, in welche wir konsekutiv 55 Patienten einschlossen, die bei AIS mittels dorsaler Korrekturspondylodese in den verschiedenen oben aufgeführten Verfahren operativ in unserem Hause versorgt wurden. In den prä- und postoperativen Röntgenbildern wurde jeweils der Cobb-Winkel der Haupt- und Nebenkurve bestimmt, sowie als Paramater für die sagittale Balance die thorakale Kyphose, die lumbale Lordose als auch die pelvic incidence ermittelt.
In ***Abbildung 4*** sind exemplarisch prä- und postoperative Röntgenbilder von mittels verschiedener Verfahren versorgten Patienten aufgeführt.

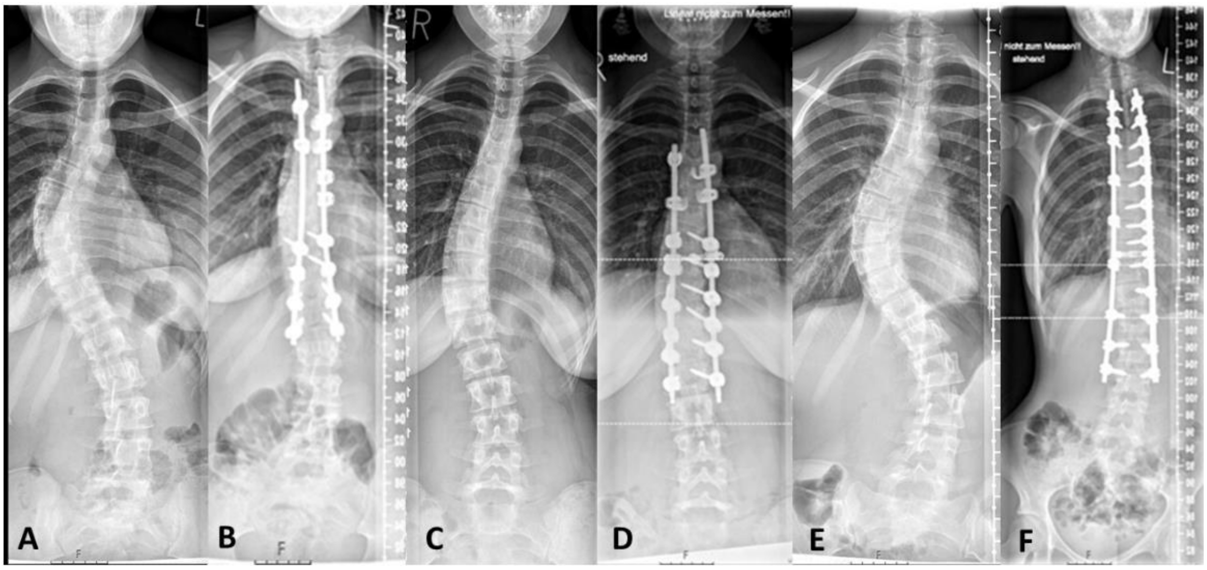


Abbildung 4. Vergleich der radiologischen Ergebnisse verschiedener Spondylodeseverfahren
Wirbelsäulenganzaufnahme eines Patienten versorgt mit Hybrid-Verfahren mit Schrauben, sublaminaren Bändern und Haken (A präoperativ, B Postoperativ), eines Patienten versorgt mit Hybrid-Verfahren mit Schrauben und Haken (C präoperativ und D postoperativ) und eines Patienten versorgt mittels „All-Screw“-Technik (E präoperativ und F postoperativ). Mit freundlicher Genehmigung durch Univ.-Prof. Dr. G. Antoch, Institut für diagnostische und interventionelle Radiologie.

Bei Betrachtung des Korrekturpotentials für Haupt- und Nebenkurven sowie für das sagittale Profil zeigten sich zwischen dem AS-Verfahren, dem HSH-Verfahren und dem HSHB-Verfahren weder umgehend postoperativ noch während des mittleren 3-Jährigen Follow-Ups signifikante Unterschiede. ***Abbildung 5*** fasst diese Ergebnisse zusammen.

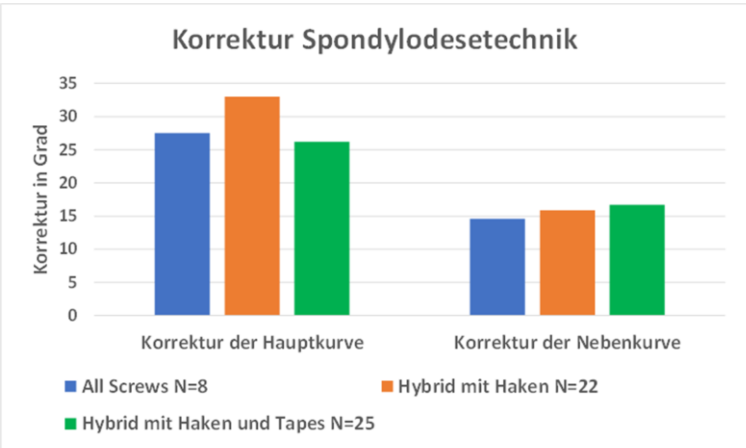


Abbildung 5. Erreichtes Korrekturpotential in Abhängigkeit der Spondylodesetechnik
Dargestellt wird das erreichte Korrekturpotential in Grad des Cobb-Winkels sowohl der Haupt- als auch der Nebenkurve in Abhängigkeit der verschiedenen Spondylodesetechniken. Eigene Abbildung.

Bezüglich des Korrekturpotentials der Hauptkurve und auch in Bezug auf das sagittale Profil zeigte sich zwischen SF und NSF ebenfalls kein signifikanter Unterschied. Bezüglich des Korrekturpotentials der Nebenkurve zeigt die NSF ein signifikant besseres Ergebnis (26,9° vs.

15,1°; $P < 0.05$). Jedoch kommt es auch durch die SF, welche mit einer deutlich kürzeren Fusionsstrecke und einer somit deutlich besseren postoperativen Beweglichkeit einhergeht zu einer Korrektur der Nebenkurve um durchschnittlich 43,9%. ***Abbildung 6*** fasst diese Ergebnisse zusammen.

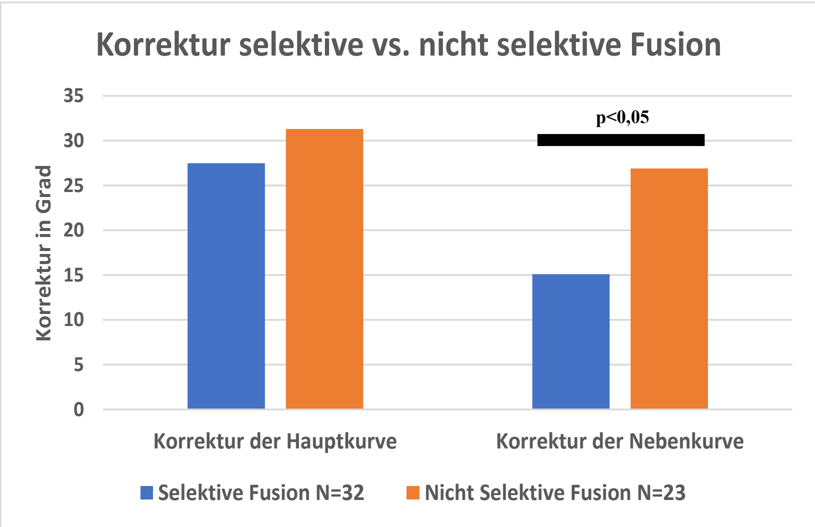


Abbildung 6. Erreichtes Korrekturpotential in Abhängigkeit der Fusionslänge
Dargestellt wird das erreichte Korrekturpotential in Grad des Cobb-Winkels sowohl der Haupt- als auch der Nebenkurve in Abhängigkeit, ob eine selektive- oder eine nicht selektive Fusion durchgeführt wurde. Eigene Abbildung.

Zusammenfassend lässt sich festhalten, dass Hybridverfahren im Vergleich zum AS- Verfahren in Bezug auf das zu erreichende Korrekturpotential als gleichwertig zu erachten sind; dass durch die NSF auf Kosten der postoperativen Beweglichkeit eine signifikant bessere Korrektur der Nebenkurve als bei der SF erreichbar ist; und dass die SF bei ausgewählten Patienten jedoch ebenso zu einer deutlichen perioperativen Korrektur, der nicht adressierten Nebenkurve um ca. 40% führt und dabei durch die kürzere Fusionsstrecke dennoch eine gute postoperative Beweglichkeit erhält.

5. Einfluss des untersten instrumentierten Wirbelkörpers auf die Korrektur der Nebenkurve im Rahmen der selektiven Fusion bei Patienten mit idiopathischer Skoliose

Prost M, Denz P, Windolf J, Konieczny MR. The Impact of the Lowest Instrumented Vertebra on the Correction of the Minor Curve During Selective Fusion in Patients with Adolescent Idiopathic Scoliosis. Clin Spine Surg. **2024**

Das unter anderem von Lenke et al. propagierte und heutzutage bei entsprechender Deformität regelhaft durchgeführte Konzept der SF basiert auf einer deutlich verkürzten

Fusion, bei welcher lediglich die strukturelle Hauptkurve adressiert wird.[11,83,84] Die nichtstrukturellen Nebenkurven korrigieren sich passiv.[85] Der Vorteil dieses Verfahrens ist eine bessere postoperative Beweglichkeit bedingt durch die kürzere Fusionsstrecke.[114,115] Elementar für den Erfolg dieses Verfahrens ist die adäquate Auswahl des LIV.[55] Bisher ist noch nicht abschließend geklärt, inwieweit sich die Auswahl des LIV auf die Korrektur der Nebenkurve, sowie auf die Korrektur der sagittalen Balance auswirkt. Dies zu untersuchen war Ziel dieser retrospektiven Arbeit.

Hierfür führten wir eine Datenanalyse durch, für welche wir konsekutiv 47 Patienten einschlossen, die bei AIS mittels dorsaler Korrekturspondylodese, durchgeführt als SF operativ in unserem Hause versorgt wurden. In den prä- und postoperativen Röntgenbildern wurde jeweils der Cobb-Winkel der Haupt- und Nebenkurve bestimmt sowie als Paramater für die sagittale Balance die thorakale Kyphose, die lumbale Lordose als auch die pelvic incidence ermittelt. Weiterhin wurden in den prä- und postoperativen Aufnahmen die Endwirbel und die stabilen Wirbel der jeweiligen Kurven, als auch der sagittale Umschlagpunkt (IP) und der Scheitelpunkt der lumbalen Lordose bestimmt. Sämtliche Parameter wurden in Abhängigkeit des jeweils gewählten LIV analysiert.

Im Rahmen der statistischen Auswertung ergab sich eine hohe Korrelation (0.701) zwischen der perioperativ erreichten Korrektur der Hauptkurve und der anschließenden passiven Korrektur der Nebenkurve. Weiterhin zeigte sich jeweils eine signifikant verbesserte Korrektur der Nebenkurve, wenn mehr als 5 Level zwischen LIV und Endwirbel oder 4 Level zwischen LIV und stabilen Wirbel der Hauptkurve lagen ($p>0{,}001$ bzw. $p>0{,}01$). Weiterhin konnte gezeigt werden, dass die Wahl des LIV mit Abstand von 2 oder mehr Wirbelkörpern vom IP eine signifikant bessere Korrektur der Nebenkurve erbrachten ($p>0{,}01$). Dies wir beispielhaft in ***Abbildung 7*** dargestellt.

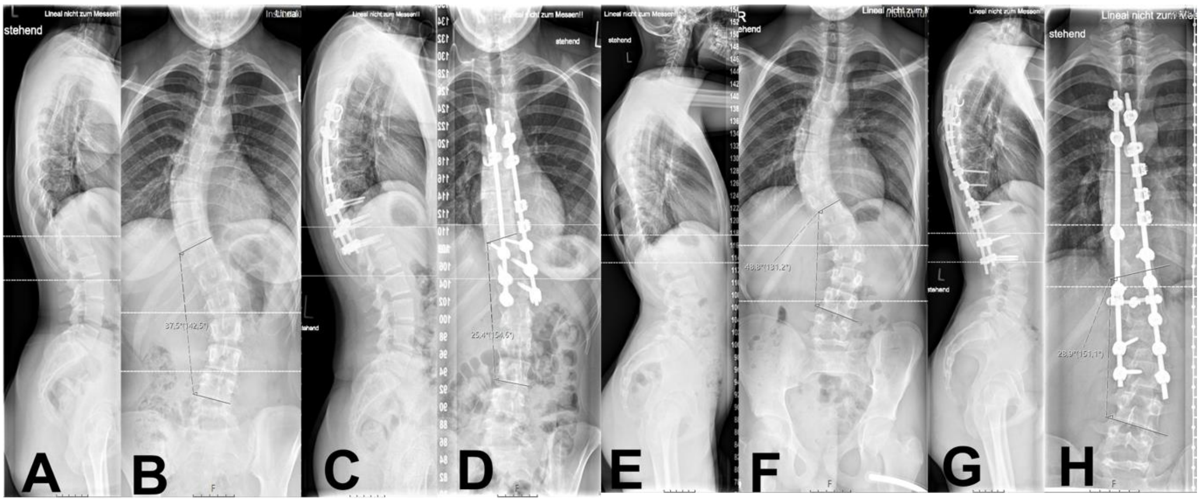


Abbildung 7. Darstellung des Einflusses des Abstandes des untersten Instrumentierten Wirbelkörpers vom sagittalen Umschlagpunkt auf die Korrektur der Nebenkurve.
Zwei Beispiele für den Einfluss des Abstandes des untersten Instrumentierten Wirbelkörpers (LIV) vom sagittalen Umschlagpunkt (IP) auf die Korrektur der Nebenkurve. In beiden Fällen wurde die Nebenkurve präoperativ als nichtstrukturell identifiziert. **A-D** zeigen die prä- und postoperativen Röntgenbilder eines Patienten bei welchen der LIV und der IP auf demselben Leven gewählt wurden. Hier wurde eine Korrektur der Nebenkurve von 37° auf 25° (32,5%) erzielt. **E-H** zeigen die prä- und postoperativen Röntgenbilder eines Patienten, bei welchem zwischen LIV und IP 3 Level Abstand gewählt wurden. Hier wurde eine Korrektur der Nebenkurve von 48° auf 28° (41,7%) erzielt. Mit freundlicher Genehmigung durch Univ.-Prof. Dr. G. Antoch, Institut für diagnostische und interventionelle Radiologie.

Zusammenfassend konnte in dieser Studie herausgestellt werden, dass nicht nur Parameter des frontalen Profils eine Rolle bei der Auswahl des LIV darstellen, sondern Parameter des sagittalen Profils bei der Auswahl des LIV berücksichtigt werden sollten. Diesbezüglich wurde durch uns hier erstmals die Relevanz des sagittalen IP bei der Wahl des LIV nachgewiesen.

6. Bovine Xenografts sind sichere Knochenersatzmaterialien bei der multisegmentalen instrumentierten spinalen Fusion

Prost M, Windolf J, Konieczny MR. Bovine-derived xenograft is a viable bone graft substitute in multilevel, instrumented, spinal fusion. Orthop Rev (Pavia). **2022**

Um eine sichere und langfristige knöcherne Fusion bei langstreckiger dorsaler Korrekturspondylodese, wie sie zum Beispiel im Rahmen der operativen Therapie von Patienten mit AIS durchgeführt wird, zu erreichen wurde lange Zeit eine dorsale Dekortikation sowie die Anlagerung von autologer Spongiosa, am ehesten vom Beckenkamm, als Goldstandard angesehen.[76,77,78] Dieses Verfahren führt zu sehr geringen Pseudarthroseraten, geht jedoch mit einer deutlich erhöhten Entnahmemorbidität einher.[78,81,82] Daher werden heutzutage regelhaft Knochenersatzmaterialen, wie zum Beispiel bovine Xenograft als

Alternative herangezogen. Es existieren bereits Daten, die den erfolgreichen und sicheren Einsatz in Bezug auf die Erzielung einer knöchernen Fusion durch diese Xenografts bei kurzstreckigen Spondylodesen belegen.[116–118] Ziel dieser Arbeit war es nun zu untersuchen ob auch bei langstreckigen Korrekturspondylodesen, wie bei der operativen Therapie der AIS üblich, durch Xenografts eine sichere Fusion erzielt und Pseudarthrosen mit sekundärem Korrekturverlust vermieden werden können.

Es wurden die Daten von 28 Patienten, bei welchen aufgrund einer AIS eine langstreckige dorsale Korrekturspondylodese durchgeführt wurde und bei welchen bovine Xenografts als Knochenersatz verwendet wurde, analysiert. Als Marker für eine Pseudarthrose bzw. eine ausbleibende knöcherne Fusion über einen Zeitraum von 2 Jahren wurde ein möglicher Korrekturverlust im Bereich der instrumentierten Hauptkurve festgelegt. Hierfür wurden die Cobb-Winkel der Hauptkurve und die thorakale Kyphose in den vorhandenen Röntgenbildern bestimmt.

Es konnte gezeigt werden, dass es nach initialer perioperativer Korrektur des Cobb-Winkels der Hauptkurve sowie der thorakalen Kyphose im Rahmen des Follow-ups über 2 Jahren zu keiner signifikanten Veränderung der gemessenen Cobb-Winkel der Hauptkurven und der thorakalen Kyphose kam und somit in beiden Ebenen kein Korrekturverlust als Marker für eine Pseudarthrose beobachtet werden konnte. Diese Ergebnisse bezüglich der Cobb-Winkel der Hauptkurven werden in ***Abbildung 8*** dargestellt.

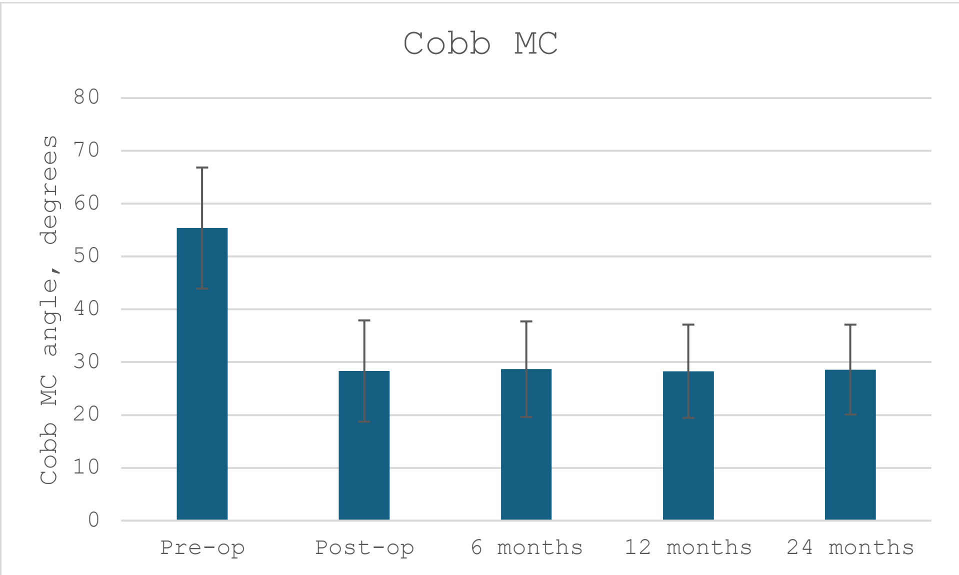


Abbildung 8. Veränderung des Cobb-Winkels der Hauptkurve perioperativ und im postoperativen Verlauf
Dargestellt wir der Cobb-Winkel der Hauptkurve (MC) in Grad sowohl präoperativ als auch umgehend postoperativ und in den Kontrollen 6, 12 und 24 Monate postoperativ. Mit freundlicher Genehmigung von Scholistica im Rahmen der Open Access Veröffentlichung unter Creative Commons Lizenz.

Zusammenfassend hat diese Studie gezeigt, dass bovine Xenografts als Knochenersatzmaterial in dem untersuchten Patientenkollektiv eine sichere Alternative zur Verwendung von autologer Beckenkammspongiosa in Bezug auf die Prävention eines etwaigen Korrekturverlust darstellt.

Diskussion

Skoliosen, insbesondere AIS sind häufig und betreffen bis zu jedes 20. Kind beziehungsweise Jugendlichen. [8] Die Tatsache, dass meist ansonsten gesunde Kinder und Jugendliche betroffen sind macht es umso wichtiger, dass die jeweilige Therapieentscheidungen auf fundierter Basis getroffen werden, da die Patienten bei fehlerhafter oder unzureichender Therapie potenziell mehrere Jahrzehnte darunter leiden müssen. So gibt es eine Vielzahl an Arbeiten, welche vermehrt Rückenschmerzen, kardiopulmonale Symptome und psychische Einschränkungen bei Patienten insbesondere mit größeren thorakalen Krümmungen beschreiben.[32,33,36,119,120] Deshalb ist es auch umso wichtiger, die gängigen Therapiekonzepte regelhaft anhand der neuesten Kenntnisse der Wissenschaft zu prüfen und weiterzuentwickeln.

So ist eine Thematik, welche aktuell Gegenstand der Forschung ist, die präoperative Planung mittels FA. Allein die Tatsache, dass über 10 verschiedene Techniken zur Anfertigung von FA beschrieben sind und basierend auf den aktuellen Daten, keine hier umfänglich in Hinsicht auf alle Gesichtspunkte den anderen Typen von FA überlegen ist, zeigt, dass hier noch weitere Untersuchungen notwendig sind. [7,37,38] Ein signifikanter Nachteil, den alle aktuell gängigen Techniken zur Anfertigung von FA gemein haben ist, dass alle mit einer zusätzlichen Strahlenbelastung für die Patienten einhergehen. Mehrere Studien belegen die im Vergleich zur Allgemeinbevölkerung erhöhte Rate an Karzinomen und eine erhöhte Tumorsterblichkeit, insbesondere im Fokus stehen hier Mamma-Karzinome [49,94,121] und Endometriumkarzinome [95]. Weiterhin sind röntgenstrahlenbedingte Schäden an der DNA von Patienten mit AIS nachweisbar. [50] Die Erforschung von Alternativen zu strahlenbelastenden nativradiologischen Aufnahmen ist somit ein elementarer Bestandteil zur Verbesserung der Therapie von Patienten mit AIS.

Im Zuge der vorgelegten Arbeiten wurde daher analysiert, ob Daten, welche im Rahmen von routinemäßig präoperativ angefertigten CT-Scans oder MRT´s genutzt werden können, um präoperative FA zu ersetzen und somit einen Beitrag zum Strahlenschutz zu leisten. Die Ergebnisse der beiden Arbeiten zeigten, dass insbesondere die Fragestellung, ob Nebenkurven struktureller oder nicht-struktureller Natur sind mit Hilfe der beiden bildgebenden Modalitäten beantwortet werden kann. [2,1] Diese Fragestellung ist wichtig, um die Deformitäten zu klassifizieren oder wenn im Rahmen der präoperativen Planung entschieden werden muss, ob eine SF durchgeführt werden kann oder nicht.[11,83] Weitere Arbeiten, welche die Ergebnisse der hier veröffentlichen Arbeiten bereits heranzogen, konnten ebenso zeigen, dass die Daten, welche aus einem präoperativen MRT oder CT generiert werden, dazu genutzt werden können die zu erwartende postoperative Korrektur vorherzusagen. [122] Weitere Informationen, welche zum Teil aus den FA gewonnen werden und welche insbesondere der Planung des LIV dienen, können die beiden bildgebenden Modalitäten, basierend auf den publizierten Ergebnissen jedoch nicht liefern. [87] Somit ist nach aktuellem Stand noch kein vollständiger Ersatz von FA möglich. Dennoch kann, wenn zum Beispiel die Planung des LIV unabhängig von FA erfolgen kann und es primär um die Beurteilung des strukturellen Charakters der Nebenkurven geht, ein präoperatives MRT die präoperativen FA ersetzen. So können die Ergebnisse dieser Arbeit einen wichtigen Baustein zur Reduktion der Strahlenbelastung liefern. Ansätze um hier die Aussagekraft eines präoperativen MRT´s gegebenenfalls noch zu erweitern stellen zum Beispiel biochemische MRT Sequenzen dar. Hier gibt es bereits Daten, dass die Bandscheiben von Patienten mit AIS hier signifikante Unterschiede im Vergleich zu einem gesunden Vergleichskollektiv aufweisen. [123]

Eine weitere hier vorgelegte Arbeit befasst sich ebenso mit der Thematik der Reduktion der Strahlenbelastung. Hier wurden insbesondere Strahlenschutzaspekte im Rahmen des Nutzens von intraoperativer Navigation beleuchtet. Der Einsatz von Navigation und Robotik wird aktuell weiterhin kontrovers diskutiert. Die Angaben zur Rate an Schraubenfehllagen für die einzelnen verschiedenen Techniken variieren stark im Rahmen der vorliegenden Literatur. So werden für die Schraubenimplantation mittels Navigation Fehllagen zwischen 1.9–11% beschrieben. [124,125] Klare Empfehlungen für die Navigation bzw. Robotik gibt es aktuell nur für den Einsatz bei komplexen Deformitäten oder Revisionseingriffen. [75] Ein Kritikpunkt an der navigierten Implantation von PS ist, dass sie vermeintlich zu einer Erhöhung der Strahlenbelastung für die Patienten führt. [126–128] Dies konnte durch die hier vorgelegte Arbeit widerlegt werden. Es konnte gezeigt werden, dass in der von uns angewandten Technik die navigierte Schraubenimplantation gegenüber dem klassischen bildwandlegestützten Verfahren (0.025 mSv vs. 0.781 mSv; $p < 0.001$) mit einer signifikanten Reduktion der Strahlendosis pro implantierter PS einhergeht. [3] Die Rate an Schraubenfehllagen zeigte sich ebenfalls signifikant reduziert. Somit konnte auch diese Arbeit mit der Bestätigung, der Sicherheit der navigierten Implantation von PS und der gleichzeitig damit einhergehenden Reduktion der Strahlenbelastung einen wichtigen Bestandteil zur Verbesserung der Versorgung von Patienten mit AIS liefern. Eine Problematik, welche die eingeschränkte Vergleichbarkeit vieler veröffentlichter Arbeiten bedingt ist, dass die Häufigkeit des Einsatzes der intraoperativen Bildgebung stark variiert und insbesondere von der genutzten Technik und Erfahrung des Operateurs abhängt. [75] Dies resultiert in deutliche Schwankungen in der dokumentierten Strahlenbelastung zwischen den verschiedenen Studien. Weiter zu beachten ist, dass die verschiedenen Geräte zur Akquirierung von intraoperativen Bildern ebenfalls alle, technisch bedingt, verschiedenen Strahlenbelastungen erzeugen. Angebracht werden muss an dieser Stelle auch der Strahlenschutzaspekt für den Operateur und das OP-Team, hier gibt es eindeutige Daten die sicher eine signifikante Reduktion der Strahlenbelastung durch den Einsatz von Navigationsverfahren belegen [101]. Letztendlich muss festgehalten werden, dass der Einsatz von Navigation im Vergleich zur bildwandlergestützten Technik nicht zwangsläufig zu einer erhöhten Strahlenbelastung für den Patienten führt, sondern dies insbesondere auch abhängig vom Operateur und seiner eingesetzten Technik sowie seiner Erfahrung ist. So kann der routinemäßige Einsatz der Navigation in Händen eines erfahrenen Operateurs gar zur Reduktion der Strahlenbelastung für die Patienten führen und gleichzeitig ebenso die Rate an Schraubenfehllagen senken.

In der hier aufgeführten Arbeit bezüglich der gewählten OP-Technik konnte gezeigt werden, dass in dem hier untersuchten Patientenkollektiv das Hybridverfahren im Vergleich zum AS-Verfahren in Bezug auf das zu erreichende Korrekturpotential als gleichwertig zu erachten war.[5] Vergleichbare Arbeiten schreiben hingegen den AS-Verfahren deutlich bessere Korrekturpotentiale in Bezug auf die Korrektur des frontalen Profils zu, welche insbesondere bei einer hohen Implantatdichte zum Tragen kommt. [65] Ob diese zusätzliche Korrektur die Lebensqualität und das Outcome der Patienten verbessert bleibt unklar. [66]Tsirikos et al. beschrieben in ihrer Untersuchung im Gegensatz dazu und ähnlich zu der hier aufgeführten Arbeit, dass mit standardisierten Hybrid-Verfahren gute Korrekturergebnisse sowie eine gute Patientenzufriedenheit erzielbar ist und weiterhin es zu einer signifikanten Reduktion der OP-Zeit, des Blutverlustes und auch der Implantatkosten kommt. [129] Dieser erhöhte Kostenaspekt für die AS-Verfahren konnte auch durch andere Autoren bestätigt werden [130]. Bezüglich der Korrektur des sagittalen Profils scheinen die Hybridtechniken den AS-Techniken geringfügig überlegen. [109,131,132]

In dem durch uns untersuchten Patientenkollektiv konnte auch über ein Follow-up von 3 Jahren kein signifikanter sekundärer Korrekturverlust und kein Unterschied in Bezug auf die Rate an Revisionseingriffen beobachtet werden [5]. Andere Arbeiten, welche ein längeres Follow up aufwiesen, zeigten jedoch eine signifikant erhöhte Rate an Revisionsoperationen bei Hybridverfahren deren Ursache dann meist eine Implantatdislokation oder eine Pseudarthrose waren [132–134]. Letztendlich lässt sich festhalten, dass Hybridverfahren eine kostengünstigere Alternative zu den AS-Verfahren sind und über welche eine adäquate Korrektur der Deformität erreicht werden kann. Der Einsatz dieses Verfahrens sollte insbesondere bei ausgeprägten Deformitäten mit stark dysplastischen Pedikeln, bei welchen eine adäquate Schraubenplatzierung häufig kaum möglich ist, in Betracht gezogen werden. Das erhöhte Risiko insbesondere an Pseudarthrosen muss berücksichtigt werden. Hier sollten insbesondere Maßnahmen zur Verbesserung der dorsalen Fusion betrachtet werden. Eine suffiziente dorsale Fusion ist insbesondere auch im Rahmen des Konzeptes der SF, welches mit kürzeren instrumentierten Strecken einhergeht, relevant.

Daher befasste sich eine Weitere der hier vorgelegten Arbeiten mit Optimierungsmöglichkeiten der dorsalen Fusion. Elementar zum Erreichen der Fusion ist neben der dorsalen Dekortikation die Anlagerung von osteoinduktivem bzw. osteokonduktivem Material. Der als lange Standard angesehene Einsatz von Beckenkammspongiosa gerät mehr und mehr in Kritik, da ihm insbesondere eine deutlich erhöhte Entnahmemorbidität einhergehend mit erhöhtem intraoperativem Blutverlust, verlängerter OP-Zeit und verstärkten postoperativen Schmerzen zugeschrieben werden. [79,81,82] Es gilt daher Alternativen zur klassischen Beckenkammspongiosaentnahme zu etablieren, da dies bedingt durch kürzere OP-Zeit, weniger Blutverlust und insbesondere durch ein geringeres postoperatives Schmerzniveau, zu einer deutlichen Verbesserung der Patientenzufriedenheit führen kann. Eine Vielzahl an verschiedenen Allografts oder Knochenersatzmaterialien werden bereits als Alternative zur Beckenkammspongiosa zur Erzielung einer dorsalen knöchernen Fusion eingesetzt. Auch für den Einsatz bei AIS gibt es schon vielversprechende Daten. [79] Die hier vorgelegte Arbeit bestätigte diese hervorragenden Ergebnisse in Bezug auf die Erreichbarkeit einer knöchernen Fusion für den Einsatz von bovinen Xenograft [6]. Vergleichbare Ergebnisse zeigte Nickoli et al. für den Einsatz von keramischen Knochenersatzmaterialien im Rahmen von lumbalen Spondylodesen [135], Weber et al. für den Einsatz von bovinen Xenografts in der Erzielung einer Fusion im Rahmen der Traumaversorgung [136] oder Garin et al. für den Einsatz von bovinen Xenografts in einem Patientenkollektiv mit gemischten Indikationen [137]. Letztendlich kann festgehalten werden, dass es eine Vielzahl von suffizienten Ersatzmöglichkeiten für den Einsatz von Beckenkammspongiosa zum Erreichen einer dorsalen Fusion gibt. Diese hier vorgelegte Arbeit stellt erstmalig heraus, dass auch bovine Xenografts eine suffiziente Ersatzmöglichkeit darstellen. Ihr Einsatz kann dazu führen, dass keine Notwendigkeit mehr zur schmerzhaften Entnahme von Beckenkammspongiosa besteht.

Zwei weitere hier vorgelegte Arbeiten befassen sich unter anderem mit der SF versus NSF und der damit einhergehenden Fragestellung nach der korrekten Auswahl des LIV. Bezüglich des Vergleichs der SF und der NSF konnte gezeigt werden, dass die NSF erwartungsgemäß ein höheres Korrekturpotential in Bezug auf die Nebenkurven hat, aber die SF auch zu einer deutlichen passiven Korrektur der Nebenkurve führt. [5] Das die NSF ein höheres Korrekturpotential auf die Nebenkurven hat wurde durch andere Autoren ebenfalls bestätigt. [113] Die deutlichen Ergebnisse unserer Arbeit bezüglich der ausgeprägten passiven Korrektur der Nebenkurve um bis zu 40 % im Rahmen der SF sind äquivalent zu den Daten welche Lenke et al. diesbezüglich präsentierten. [83,85] Zum Erreichen einer guten Patientenzufriedenheit ist nicht ein maximales Korrekturergebnis, wie es bei der NSF der Fall wäre, notwendig. [66]

Die kürzere Fusionsstrecke im Rahmen der SF geht mit nachweisbaren Vorteilen einher, so ist zum Beispiel die Länge der Fusionsstrecke ein klarer Einflussgeber auf die Möglichkeit zur Rückkehr zum Sport [60]. Weiter konnte gezeigt werden, dass längere Fusionsstrecken bei Frauen die Wahrscheinlichkeit zur Notwendigkeit eines Kaiserschnittes erhöhen. [61] Mehrere aktuelle Reviews stellten nochmals heraus, welchen Stellenwert neben der Korrektur des frontalen Profils auch die adäquate Wiederherstellung der sagittalen Balance im Rahmen der operativen Therapie hat, insbesondere auch in Hinblick auf die anschließende Patientenzufriedenheit [138,139]. Hier konnte durch die vorgelegte Arbeit nachgewiesen werden, dass zum Erreichen eines adäquaten sagittalen Profils nicht eine langstreckige Fusion im Sinne einer NSF notwendig ist. Auch durch die SF lässt sich eine suffiziente Korrektur des sagittalen Profils erzielen. [5] Somit kann der SF neben der kürzeren Fusionsstrecke auch eine suffiziente sagittale Korrektur als wichtiger Parameter der Patientenzufriedenheit zugeschrieben werden.

Schlussendlich lässt sich festhalten, dass die SF insbesondere für ausgewählten Kurventypen ein sicheres Verfahren ist. Das Verfahren führt zu einer guten Korrektur der Haupt- und auch der Nebenkurven sowie auch des sagittalen Profils und erhöht letztendlich die Patientenzufriedenheit. Unabdinglich für den Erfolg der SF ist die richtige Identifikation des LIV. Die präoperative Identifikation des am besten geeigneten LIV gestaltet sich weiterhin komplex. Es soll auf der einen Seite erreicht werden die instrumentierte Strecke so kurz wie möglich zu halten, um eine bestmögliche postoperative Beweglichkeit zu erreichen und auf der anderen Seite muss ein sekundärer Progress der Deformität, bedingt durch eine zu kurze instrumentierte Strecke, vermieden werden. Es gibt eine Vielzahl an Arbeiten, die verschiedenste radiologische Parameter zur Identifikation des LIV benennen. [56–58,83,84,86,88,140] Liu et al. stellen zudem in ihrem Review aus 2020 dar, dass neben den radiologischen Parametern auch immer die gewählte Operationstechnik einen Einfluss auf die adäquate Auswahl des LIV hat, was die Auswahl noch weiter erschwert. [141]

Fast alle der benannten radiologischen Richtwerte sind Parameter des frontalen Profils. Die hier vorgelegte Arbeit präsentiert nun mit dem sagittalen IP einen relevanten Parameter des sagittalen Profils, welcher basierend auf den Daten ebenfalls zur Identifikation des korrekten LIV herangezogen werden sollte. [4] Die Relevanz der Beachtung des sagittalen Profils im Rahmen der operativen Therapie wurde bereits weitgehend belegt. [138,139] Somit ist es aus unserer Sicht elementar das sagittale Profil in die präoperative Planung miteinzubeziehen.

Rizkallah et al. verglichen verschiedene Verfahren zur Auswahl des LIV miteinander und konnten zeigen, dass es anhand verschiedener Verfahren häufig zur Identifikation von unterschiedlichen LIVs kam. [87] Sie kommen weiter zu dem Schluss, dass der LIV, welcher übereinstimmend durch die meisten Verfahren identifiziert wird in der Regel auch der LIV war, welcher postoperativ zu den besten Resultaten führte. In Bezug auf die Einzelverfahren konnte dieser LIV am häufigsten durch die Methodik nach Dubousset identifiziert werden. Diese Methodik ist eine der wenigen, die bereits zuvor auch mit der Bewertung der segmentalen Kyphose im lateralen Röntgenbild einen Parameter des sagittalen Profils mit in die Findung des LIV einbezieht. [87]

Letztendlich konnte aktuell noch kein ein-eindeutiger Parameter zur Auswahl des richtigen LIV festgestellt werden, multiple radiologische Parameter sowie auch das geplante operative Vorgehen müssen berücksichtigt werden. Insbesondere aber auch Parameter des sagittalen Profils sollten Einfluss in die Auswahl des LIV finden, um die dreidimensionalen Eigenschaften einer Skoliose dazustellen. Hier konnte die vorgelegte Arbeit erstmalig den sagittalen IP als relevanten Marker für die Auswahl des LIV zur Optimierung der Durchführung einer SF präsentieren. Die biochemisch sensitive MRT-Bildgebung zur verbesserten und frühzeitigen Beurteilung von strukturellen Veränderungen der Bandscheiben kann in Zukunft eventuell weitere Parameter liefern, die die Auswahl des geeignetsten LIV vereinfachen.

Schlussfolgerung und Ausblick

Die hier dargestellten und diskutierten Arbeiten konnten zeigen, dass bei Vorliegen eines präoperativen MRT´s oder präoperativen CT-Scans in Bezug auf die Fragestellung, ob Nebenkurven struktureller oder nicht- struktureller Natur sind, auf FA verzichtet werden kann und so zur Reduktion der Strahlenbelastung der Patienten beigetragen werden kann. Es konnte auch gezeigt werden, dass der Einsatz der Navigation im Rahmen der Implantation von Pedikelschrauben zur Reduktion der Strahlenbelastung für die Patienten führen und gleichzeitig ebenso die Rate an Schraubenfehllagen senken kann. Es konnte auch gezeigt werden, dass Hybridverfahren eine kostengünstigerer Alternative zu den AS-Verfahren sind und über diese eine adäquate Korrektur der Deformität erreicht werden kann. Der Einsatz dieser Verfahren sollte insbesondere bei ausgeprägten Deformitäten mit stark dysplastischen Pedikeln in Betracht gezogen werden.

Ebenso wurde dargestellt, dass es mit bovine Xenografts ein weiteres suffizientes Knochenersatzmaterial zum Erreichen einer knöchernen Fusion im Rahmen der operativen Therapie von Skoliosen gibt, welches die schmerzhafte Entnahme von Beckenkammspongiosa unnötig machen kann.

Die SF wurde als sicheres Verfahren für ausgewählt Kurventypen bestätigt, welches durch eine Verkürzung der instrumentierten Strecke und durch eine adäquate Korrektur des sagittalen Profils zwei elementare Faktoren in Bezug auf die langfristige Patientenzufriedenheit positiv beeinflusst.

Abschließend konnte noch dargelegt werden, dass bei der für die SF elementaren korrekten Identifikation des LIV unabdingbar ist das sagittale Profil zu berücksichtigen. Diesbezüglich wurde der sagittale IP erstmals als relevanter Parameter benannt.

Die biochemisch sensitive MRT-Bildgebung zur verbesserten und frühzeitigen Beurteilung von strukturellen Veränderungen der Bandscheiben kann in Zukunft eventuell weitere Parameter liefern, die die Auswahl des geeignetsten LIV vereinfachen und gleichzeitig zur weiteren Reduktion der Strahlenbelastung beitragen.

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Danksagung

Es gibt viele Menschen, die mich in der Erstellung der vorliegenden Arbeit begleitet haben und denen ich an dieser Stelle meinen Dank sagen möchte.

Mein erster Dank gilt meinem Chef und Klinikdirektor Herrn Univ.-Prof. Dr. med. Joachim Windolf. Er stand mir sowohl bei der klinischen als auch wissenschaftlichen Tätigkeit stets bei, ermutigte mich immer die nächsten Schritte zu gehen und schenkte mir dabei stets seine uneingeschränkte Unterstützung.

Ein großer Dank geht auch an Herrn PD Dr. med. Markus Konieczny, welcher mich kurz nach meinem Berufsstart sowohl klinisch als auch wissenschaftlich an die Hand nahm und mir half hier meine ersten Schritte zu gehen. Ohne diesen wichtigen Grundstein wäre ich heute nicht da, wo ich jetzt stehe.

Ein ebenso großer Dank gilt Herrn Prof. Dr. med. Max Scheyerer, mit welchem ich in den letzten Jahren sowohl klinisch als auch wissenschaftlich eng zusammengearbeitet habe. Er hat mir geholfen, mich auf beiden Feldern stetig weiterzuentwickeln und ist dabei zu einem guten Freund und Vertrauten geworden.

Allen nicht namentlich genannten Kolleginnen und Kollegen der Klinik für Orthopädie und Unfallchirurgie, vor allem dem Team der Fach- und Assistenzärzte, möchte ich ausdrücklich für die großartige Zusammenarbeit und den unzerbrechlichen Teamgeist in den letzten Jahren danken. Ohne euch wären manch anstrengende schwere Stunden in der Klinik kaum zu meistern gewesen.

Ebenso möchte ich dir lieber Michael danken. Ohne den bedingungslosen Rückhalt durch dich, wäre es mir nicht möglich gewesen diese Arbeit zu schreiben und die dafür nötigen Schritte zu gehen. Du unterstützt und motivierst mich in jeder Lebenslage.

Abschließend möchte ich meinen Eltern, Angelika Prost und Ludger Prost, sowie auch meinen Großeltern, die leider nicht mehr unter uns Weilen, für ihre Unterstützung danken. Von klein auf habt ihr immer zu mir gestanden und mich unterstützt. Ihr seid das Fundament für alles, was ich in meinem Leben bisher erreichen konnte.

Danke

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Düsseldorf, den 20.10.2024 Dr. med. Max Prost

Anlagen

Beitragende Originalarbeiten

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Bezüglich der Publikation „**Prost M,** Denz P, Windolf J, Konieczny MR. The Impact of the Lowest Instrumented Vertebra on the Correction of the Minor Curve During Selective Fusion in Patients with Adolescent Idiopathic Scoliosis. Clin Spine Surg. **2024** Sep 3. doi: 10.1097/BSD.0000000000001686. Epub ahead of print. PMID: 39226153" wurde durch den Verlag Wolters Kluwer lediglich der Abdruck des finalen peer reviewed Manuskriptes genehmigt.

INTERNATIONAL JOURNAL of SPINE SURGERY

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Int J Spine Surg 2024, 18 (3) 322-328
doi: https://doi.org/10.14444/8602
https://www.ijssurgery.com/content/18/3/322

The International Journal of Spine Surgery
2397 Waterbury Circle, Suite 1,
Aurora, IL 60504, Phone: +1-630-375-1432

International Journal of Spine Surgery, Vol. 18, No. 3, 2024, pp. 322–328
https://doi.org/10.14444/8602

Impact of Different Operative Techniques for Patients With Adolescent Idiopathic Scoliosis on Frontal Curve Correction and Sagittal Balance

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ABSTRACT

Background: Surgical correction of adolescent idiopathic scoliosis from the posterior approach can be performed by the "all screws" technique; hybrid technique with screws and hooks; hybrid technique or with screws, hooks, and tapes; or selective fusion (SF) or nonselective fusion (NSF). The aim of the present investigation was to analyze the influence from different operative techniques on frontal curve correction and sagittal profile in patients with adolescent idiopathic scoliosis.

Methods: We conducted a retrospective analysis on 55 consecutive patients with scoliosis who had been treated by posterior instrumented fusion. We collected demographic data and analyzed pre- and postoperative radiographs. Statistical analysis was performed using SPSS version 25. Because data showed normal distribution, *t* tests were performed.

Results: Twenty-two patients were treated using the hybrid technique with screws and hooks; 25 were treated using the hybrid technique with screws, hooks, and tape; and 8 were treated using the all screws technique. An SF was performed in 32 patients and NSF in 23 patients. There was no significant difference with regard to curve correction of the main curve between the different techniques. Correction of the minor curve was significantly higher in NSF than in SF patients. In SF, there was a correction of the minor curve of 43.9%. Impact on sagittal balance showed no significant differences between NSF and SF.

Conclusion: The different operative techniques did not show a difference with regard to the correction of the main curve. NSF showed a significantly higher degree of correction of the minor curve than SF. However, we still found a correction of 43.9% of the noninstrumented minor curve in SF. Thus, SF and hybrid techniques do not lead to inferior radiographic outcome.

Clinical Relevance: SF and hybrid techniques are safe and effective techniques that could be used as an alternative to NSF and all screw fixation in the operative treatment for scoliosis.

Level of Evidence: 3.

Biomechanics

Keywords: Scoliosis, Selective Fusion, Treatment Strategies, frontal profile, sagittal profile

INTRODUCTION

Adolescent idiopathic scoliosis (AIS) is a deformity of the spine with an incidence of 5%.[1] Depending on the degree of the deformity assessed by the Cobb angle, conservative or operative therapy is recommended.[2] According to the Lenke classification, scoliotic curves can be classified as structural or nonstructural.[3,4] Based on this knowledge, the concept of selective fusion (SF) in the surgical treatment of AIS first explained by King et al was refined.[5] The premise of SF is that after fixation of the primary structural curve, there is spontaneous coronal correction of the unfused nonstructural curve.[6]

The existing data on the correction potential of the unfused nonstructural curve vary widely.[7] Saramuzzo et al described the stability of the correction and the improvement of clinical outcome scores over a 10-year follow-up for patients who underwent SF.[8] Furthermore, investigations have shown that patients who underwent SF show a higher level of postoperative flexibility and movement compared with those who underwent nonselective fusion (NSF).[9]

However, other investigations showed that SF compared with NSF led to a minor correction of the nonstructural curves.[10,11] According to the subjective perception of the patients, Bizzoca et al showed that although the SF provides better functional outcomes, female patients receiving SF reported a worse perceived body image compared with patients treated with NSF.[12]

Surgical correction from the posterior can be performed by an all screws technique (AS), hybrid technique with screws and hooks (HTH), or hybrid technique with screws, hooks, and tapes (HTHT).[13–19]

Current data on the correction potential of the different techniques vary widely and are inconclusive. Some investigations showed that hybrid techniques (HTs) are superior compared with AS techniques with regard to the correction of the frontal and sagittal profile.[14] Other authors reported that the AS technique is better than HT with regard to the correction of the frontal and sagittal profile.[16,17] Other investigations showed that AS was superior with regard to the correction of the frontal profile and that HT was superior with regard to the correction of the sagittal profile.[15,18,19] Considering these inconclusive data on SF vs NSF and on AS vs HT, we performed an investigation with a focus on the impact of these operative techniques on frontal curve correction and sagittal balance in patients with AIS.

MATERIALS AND METHODS

The present study was designed as a retrospective single-center data analysis. We identified consecutive patients who were treated surgically for scoliosis in our department between January 2005 and January 2020, in the clinical documentation system by diagnostic code.

We included patients with AIS who underwent surgical treatment by posterior instrumented fusion and had a complete set of data including full spine x-rays in posterior-anterior and lateral view before and after the surgery, at the end of the follow-up, and at a follow-up of at least 24 months. We excluded patients with other types of scoliosis than AIS and those who underwent previous treatment with a growing rod system. Patients with an incomplete set of data or a follow-up of less than 24 months were also excluded. Inclusion and exclusion criteria are summarized in Table 1.

We recorded demographic information data such as sex and age and documented the Lenke classification of the included patients. We assessed if the correction spondylodesis was performed as SF or NSF. Furthermore, we analyzed the performed surgical techniques: AS, HTH, and HTHT. The number of implants for each patient was recorded, and implant density was calculated. When every pedicle, for example, lamina, was equipped with an implant, the implant density was given as 1.

Only polyaxial screws and lamina hooks were used. When used in the most cranial level, the hooks were always implanted from the cranial approach in the uppermost level on the convex side and from the caudal approach on all other levels. When hooks were used, they were only used in the 2 or up to 4 most cranial segments of the instrumented part of the spine, never at the lowest instrumented vertebra. Sublaminar tapes were only used in the region of the apex of the addressed part of the deformity. Tapes have mostly been applied at the concave side of the deformity, but in some cases (16%; 4/25), they were applied at the convex part as well. Examples of pre- and postoperative full-spine radiographs from patients treated with the different techniques are shown in Figures 1 and 2.

We analyzed the full-spine standing and bending radiographs with the IDS 7-PACS-System (Sectra, Linköping, Sweden).

The Cobb angles of the main curve and of the upper and lower minor curves were measured. We also analyzed the trunk shift in the frontal plane by measuring the distance between the proc spinous of C7 to the central sacral vertical line. End vertebra, stable vertebra, and lowest instrumented vertebra were recorded. The thoracic kyphosis (TK), lumbar lordosis, and pelvic incidence were measured. Some of the performed measurements are shown in Figures 3–5.

Statistical analysis was performed by SPSS 25 (IBM, Armonk, USA). Descriptive data are given as means and SEMs. We tested all continuous variables for normal distribution by Kolmogorov-Smirnov tests. All variables showed normal distribution. Thus, we performed 1-way analysis of variance and *t* tests.

This study was approved by the local ethics committee (Register number 4948) and was conducted according to the revised Declaration of Helsinki.

Table 1. Inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Treatment	Surgical treatment by posterior instrumented fusion	Additional anterior surgical procedure or previous treatment with a growing rod system
Scoliosis type	Adolescent idiopathic scoliosis	Nonidiopathic scoliosis (ie, early-onset or neuromuscular)
Data set	Complete set of data including full spine x-rays in posterior-anterior and lateral views before and after surgery and at end of follow-up	Incomplete set of data
Follow-up	≥24 months	<24 months

RESULTS

We identified 241 consecutive patients who were treated surgically for AIS in our institution between January 2002 and January 2020 by diagnostic code. After applying the inclusion and exclusion criteria, we enrolled 55 patients in our investigation. Forty-seven patients were women (85.5%) and 8 were men (14.5%). The mean age at the time of surgery was 14.71 (1.04) years. The curve types of the included patients according to the Lenke classification are shown in Table 2.

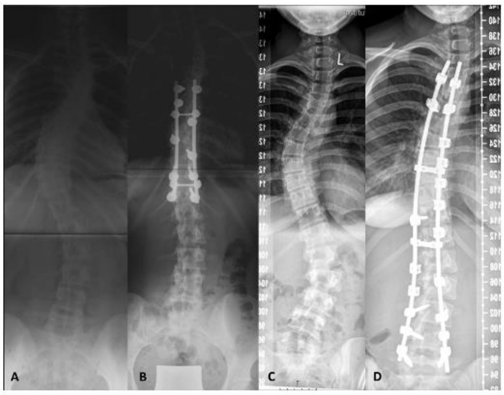

Figure 1. Example full-spine radiographs of a patient treated with selective fusion (A, presurgery and B, postsurgery) and a patient treated with nonselective fusion (C, presurgery and D, postsurgery).

Twenty-two (40.0%) patients were treated by HTH, 25 (45.5%) patients were treated by HTHT, and 8 (14.5%) patients were treated by AS. In 32 patients (58.2%), an SF was performed, and in 23 patients (41.8%), an NSF was performed. Of the 8 patients who underwent AS, 6 were SF cases and 2 were NSF.

The implant density in patients treated by AS technique was 0.90 (0.10), by HTH technique was 0.69 (0.13), and by HTHT technique was 0.80 (0.09). Only the difference in implant density between the AS technique and the HTH technique showed significance ($P < 0.05$).

Table 3 shows the Cobb angles of the main and minor curves in the pre- and postoperative radiographs as well as the correction of the Cobb angle that was achieved by the different techniques.

The difference with regard to the correction of the main curve between HTH, HTHT, and AS as well as for NSF and SF was not significant ($P > 0.05$). Correction of the minor curve was significantly higher in NSF than in SF ($P < 0.05$). In SF, there was a correction of the (noninstrumented) minor curve of 15.1° (1.60°), which means a correction of 43.9% on average.

Table 4 shows the difference between lumbar lordosis and pelvic incidence before and after surgery for the different techniques. The correction of the sagittal balance showed no significant differences between NSF and SF ($P > 0.05$).

The average difference between the Cobb angle of the main curve in the preoperative radiographs and the preoperative bending was 24.06° (10.63°) and between the Cobb angle of the main curve in the pre and postoperative radiographs was 30.33° (10.76°). This difference showed a highly significant correlation ($P < 0.001$; correlation coefficient 0.484).

There were no significant changes of these parameters during the median follow-up of 36.61 (5.19) months. During this follow-up, none of the patients in the SF or NSF subgroups had a documented case of proximal or

Figure 2. Example full-spine radiographs of a patient treated with hybrid-technique with screws, hooks, and tapes (A, presurgery and B, postsurgery); a patient treated with hybrid-technique with screws and hooks (C, presurgery and D, postsurgery); and a patient treated with all-screw technique (E, presurgery and F, postsurgery).

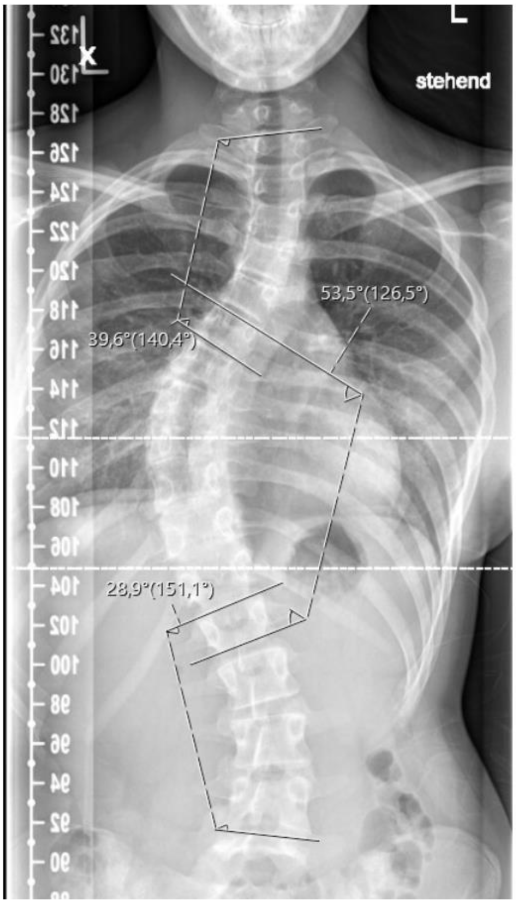

Figure 3. Measurement of the Cobb angle from the main curve and the upper and lower minor curve in a posterior-anterior view of a full-spine radiograph.

distal junction kyphosis. No patient required revision surgery.

DISCUSSION

In this investigation, we analyzed the data of 55 patients to investigate the impact of SF and NSF as well as AS, HTH, and HTHT techniques on frontal curve correction and sagittal balance in patients with AIS.

The demographic data of our group of patients with an average age of 14.71 years and a female predominance, as well as the average preoperative Cobb angles and curve types, are comparable to data reported in other recent investigations.[8–19] This seems to indicate that our study population may be representative.

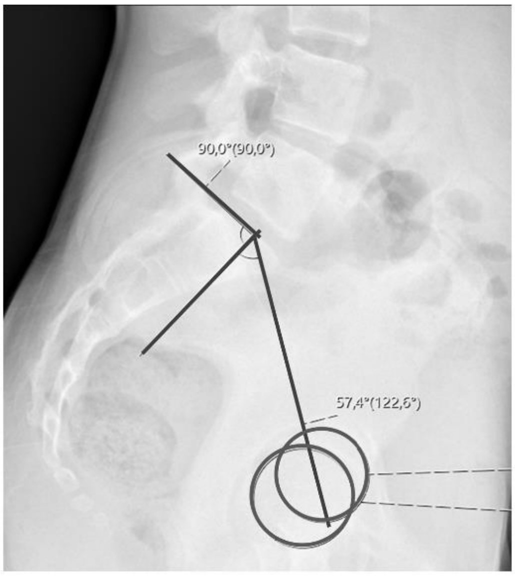

Figure 4. Measurement of the pelvic incidence in a lateral lumbar spine radiograph.

In our group of patients, the HT and the AS techniques did not show a difference that was significant with regard to the correction of the main curve. This result is comparable to the results from Tsirikos and McMillan, who reported that HT leads to comparable results with regard to the correction of the frontal profile and a superior correction of TK and of the sagittal balance than the AS technique.[14] An advantage of our investigation over the results of Tsirikos and McMillan is that we analyzed the impact of the different techniques on patients with different curve types according to the Lenke classification.

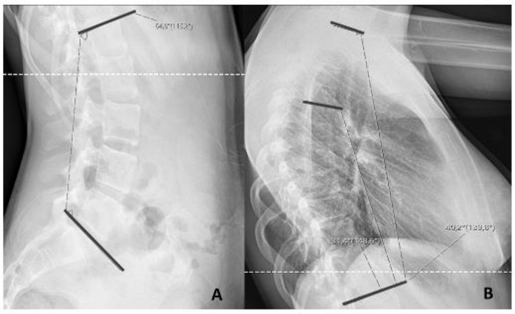

Figure 5. Measurement of parameters from the sagittal profile. (A) Measurement of the lumbar lordosis between L1 and S1 in a lateral lumbar spine radiograph. (B) Measurement of the thoracic kyphosis between T1 and T12 as well as between T5 and Th12 in a lateral thoracic spine radiograph.

Table 2. Lenke classification of included patients (N = 55).

Type of Curve	*n*	%
1	21	38.2
2	21	38.2
3	2	3.6
4	3	5.5
5	7	12.7
6	1	1.8

However, there are also recent investigations that show different results compared with our investigation. Ruiz et al showed in their retrospective analysis that in their group of patients, HT led to less curve correction in the frontal than AS.[16] However, they included patients who underwent all hooks instrumentation without any screw instrumentation. There are already data that show that the hooks-only technique leads to a poorer outcome than the modern HT or AS techniques.[20,21]

Luo et al stated that compared with HT, AS provides better coronal correction but less TK restoration, with a decreased incidence of overall complications and reoperations in AIS patients.[18] In our group of patients, we did not observe the reported higher rate of complications and reoperations in patients who were treated with HT instead of AS.

A further parameter that has to be mentioned is that the AS technique leads to a higher cost per fused level and per degree of correction compared with HT.[22] This fact may have been caused by the higher implant density in cases treated with AS technique compared with the HT technique. Comparable to existent data, in our group of patients, the NSF showed a significantly higher correction of the minor curve than SF.[10] However, we still found a correction of 43.9% of the noninstrumented minor curve in SF. Furthermore, the impact on sagittal balance showed no significant differences between NSF and SF in our group of patients. Considering SF does lead to a lower rate of complications because less segments are instrumented, we believe that SF is a good and safe alternative for selected patients.

Table 4. Difference between preoperative and postoperative LL and PI for the different techniques.

Technique	Preoperative	Postoperative	Pre- and Postoperative
All			
Mean	5.8073	4.1262	1.3875
SEM	1.94256	2.39210	2.46151
NSF			
Mean	6.54	0.36	6.18
SEM	3.25	3.78	3.34
SF			
Mean	5.47	5.81	-0.92
SEM	1.83	2.39	2.56

Abbreviations: LL, lumbar lordosis; PI, pelvic incidence.

A correction of the Cobb angle in the frontal plane that exceeds the degree of correction that is achieved by bending radiographs may lead to loss of balance and negative impact on the not instrumented minor curves.[23] In our group of patients, we found a significant correlation between the preoperative bending radiographs and the surgically achieved correction.

A limitation of our investigation is that we performed a retrospective data analysis. However, due to standard operating procedures in our department for the surgical treatment of AIS, the treatment of the patients is comparable.

Table 3. Cobb angles of the main and minor curve in the pre- and postoperative radiographs and the perioperative correction of the Cobb angle by the different techniques.

	Preoperative Cobb Angle, °		Postoperative Cobb Angle, °		Correction of Cobb Angle, ° (%)	
Technique	Main Curve	Minor Curve	Main Curve	Minor Curve	Main Curve	Minor Curve
All						
Mean	57.26	42.23	27.95	22.20	30.33 (52.9)	20.03 (47.4)
SEM	1.81	1.81	1.60	1.49	1.45	1.74
SF						
Mean	55.50	34.36	27.43	22.93	27.53 (49.6)	15.10 (43.9)
SEM	2.15	1.50	1.83	1.90	1.61	1.60
NSF						
Mean	59.72	43.99	28.37	21.18	31.35 (52.3)	26.90 (61.2)
SEM	3.00	3.47	2.68	2.34	2.36	2.92
HTH						
Mean	61.57	44.00	28.57	20.12	33.00 (53.6)	25.94 (59.0)
SEM	3.18	3.55	2.87	2.38	2.41	3.36
HTHT						
Mean	53.37	33.52	26.46	22.63	26.22 (48.9)	16.58 (49.5)
SEM	1.86	1.83	1.72	1.87	1.66	1.65
AS						
Mean	57.59	38.15	30.05	26.58	27.54 (47.8)	14.58 (38.2)
SEM	5.46	2.62	4.48	4.74	3.36	2.89

Abbreviations: AS, all screws technique; HTH, hybrid technique with screws and hooks; HTHT, hybrid technique with screws, hooks, and tapes; NSF, nonselective fusion; SF, selective fusion.

CONCLUSION

The HTs and AS did not show a difference that was significant with regard to the correction of the main curve in our group of patients. NSF showed a significantly higher degree of correction of the minor curve than SF. However, we still found a correction of 43.9% of the noninstrumented minor curve in SF. This seems to show that SF and HTs do not lead to worse radiographic outcomes than NSF and AS in carefully selected patients.

ACKNOWLEDGMENTS

The included patients were treated in different departments of the university hospital Duesseldorf inter alia from 2002 up to July 2019 in the Department for Orthopedic Surgery (Dr. Krauspe) and since August 2019 in the Department of Orthopedic and Trauma Surgery (Dr. Windolf). Some of the results published in this work were part of the PhD thesis from Philip Denz. In partial fulfillment of the requirements for a PhD thesis for Philip Denz.

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Funding: No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

Declaration of Conflicting Interests: M.R.K. reports paid lectures for Globus Medical and Depuy Synthes. The other authors declare no conflict of interest relevant to this work.

Ethics Approval: This study was approved by the local ethics committee (Register number 4948) and was conducted according to the revised Declaration of Helsinki.

Data availability statement: The data sets generated during and/or analyzed during the current study are not publicly available due data protection but are available from the corresponding author upon reasonable request.

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Published 05 June 2024

European Spine Journal (2023) 32:1771–1776
https://doi.org/10.1007/s00586-023-07659-8

ORIGINAL ARTICLE

May bending radiographs be replaced by magnetic resonance imaging in patients with adolescent idiopathic scoliosis?

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Received: 29 November 2022 / Revised: 28 February 2023 / Accepted: 16 March 2023 / Published online: 29 March 2023

Abstract

Purpose There is no data that shows if it is possible to determine if a curve is structural or non-structural or to assess flexibility of an adolescent idiopathic scoliosis (AIS) by magnetic resonance imaging (MRI) instead of bending radiographs (BR). We investigated if the results of BR may be compared to those of MRI.

Methods We retrospectively analyzed prospectively collected data of patients with AIS in whom a selective spinal fusion was performed and in whom a MRI, BR and full-spine X-rays were obtained preoperatively. We measured the Cobb angles of the main and of the minor curve in full-spine X-ray (FSR), BR and MRI and analyzed the degree of the intervertebral disk degeneration in the MRI.

Results After applying inclusion and exclusion criteria, 25 patients were included. We found a significant correlation ($p<0.05$, Corr Coeff = 0.41) between the Cobb angle of the main curve in FSR and the Cobb angle of the main curve in the MRI and between the Cobb angle of the minor curve in FSR and the Cobb angle of the minor curve in the MRI ($p<0.001$, Corr Coeff = 0.04). All patients with a minor curve of less than 25° in the BR had a Cobb angle of less than 30° in the MRI.

Conclusion Spinal curves showed a significant correlation between bending radiographs and recumbent images (MRI). In our group of patients, a Cobb angle of the minor curve of less than 30° in the MRI indicated that this minor curve was non-structural according to the classification of Lenke.

Keywords Adolescent idiopathic scoliosis · Bending radiographs · Radiation protection · Selective spinal fusion, magnetic resonance imaging

Abbreviations

AIS	Adolescent idiopathic scoliosis
LIV	Lowest instrumented vertebra
BR	Bending radiographs
CTS	Preoperative CT scan
MRI	Magnetic resonance imaging
PPR	Push-prone radiographs
IVD	Intervertebral disk
PIN	Pedicle screw insertion guided by navigation
FSR	Full-spine X-ray in posterior–anterior view
ISE	Intervertebral space below the end vertebra of the main curve
FFI	Frist flexible intervertebral space below the main curve
SEM	Standard error of mean
Corr Coeff	Correlation coefficient
p	Level of significance

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Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity of the spine. AIS has an incidence of 5% [1]. The degree of the deformity can be graded by the Cobb angle. Depending on the degree of the deformity, conservative or operative therapy is recommended [2]. A common technique for operative therapy of AIS is the selective spinal fusion. To perform selective spinal fusion, a prior discrimination of structural and non-structural curves of the total deformity according to the Lenke classification [3, 5] is important.

Furthermore, the appropriate lowest instrumented vertebra (LIV) must be determined. [3, 4]. Bending radiographs (BR) of the spine are necessary to classify a deformity according to the Lenke classification. Spinal curves, which can be corrected to less than 25° in a bending radiograph, are classified as "non-structural" [5]. A further information that is obtained by BR is the possible potential for correction of the deformity by surgery [6, 7]. Different types of bending radiographs are described in literature: push-prone radiographs (PPR) [8], fulcrum bending radiographs [6], supine side bending radiographs [9] and radiographs with traction under general anesthesia [10]. A disadvantage of all types of BR is that they lead to an additional amount of exposure to radiation for the patient and some of them, like the push-prone radiographs, lead to an additional amount of radiation to the medical personal, too.

Numerous radiographs are usually performed during conservative or operative treatment of AIS. The cumulative effective dose of standard radiographs, performed for diagnosis and follow-up of scoliosis, correlates with incidence of breast cancer in scoliosis patients and with an increasing incidence for infertility [11, 12]. Therefore, it seems to be relevant to reevaluate the need of each radiograph performed during the treatment of AIS. According to this, we wanted to analyze if the flexibility of the spine can be evaluated without BR. Some surgeons perform a MRI if AIS is treated by surgery. Since this imaging technique is performed recumbent, the difference between Cobb angles in standing or recumbent position could be evaluated to analyze flexibility.

Previous investigations of our study group showed that Cobb angels of push-prone bending radiographs (PPR) show a significant correlation with Cobb angles in preoperative CT scan (CTS) and that a Cobb angle of a minor curve in a CTS of less than 35° determined a non-structural curve. [13]

To our knowledge, there is no data that shows if it is possible to determine if a curve is structural or non-structural by MRI. If this would be possible, preoperative MRI could theoretically replace BR. This could lead to a reduction of the exposure to radiation for the patient and for the medical personnel.

We conducted this investigation to analyze if MRI instead of BR could provide information on flexibility and type of curves in patients with AIS.

Patients and methods

We retrospectively analyzed prospectively collected data in a single-center study. In our clinical documentation system, we identified consecutive patients in whom an operative treatment for AIS was performed from 04/2017 to 04/2021 by diagnostic code. We included patients who were treated by a selective spinal fusion with PIN and who had a full-spine X-ray in posterior–anterior view (FSR), BR and MRI in the preoperative planning. In our institution, PPR are performed as BR. We excluded patients with incomplete sets of radiological data. We recorded demographical data like sex and age, and recorded the Lenke classification of the included patients.

The radiographs were analyzed by the IDS 7-PACS®-System (Sectra, Linköping, Sweden). In all available radiographs (FSR, PPR and the MRI), the Cobb angle of the main curve and of the upper and lower minor curve was measured. Furthermore, we measured the segmental Cobb angle of the intervertebral space under the lowest vertebra of the main curve (ISE) and the angle of the first flexible intervertebral space below the main curve (FFI). Measurement of Cobb angle in the MRI is demonstrated in (Fig. 1). Measurement was performed in coronal reconstructions of the MRI. Due to the 3D character of the spinal deformity in patients with scoliosis in the performed MRI scans, there were no single slides, i.e., no single images, which showed the entire curve of a patient. Thus, to gain more comparability between the patients, we decided to perform the measurement of the Cobb angle in the way we presented in Fig. 1. End vertebras were identified in the FSR. The angle between the superior endplate of the cranial end vertebra and the horizontal plane and the angle between the inferior endplate of the caudal end vertebra and the horizontal plane were measured. These two angles were added to obtain the Cobb angle of the according curve (Fig. 1).

Identification and measurement of the ISE and the FFI

The lowest intervertebral space of the main curve was defined as the intervertebral space between the caudal end vertebra of the main curve and the cranial end vertebra of the caudal minor curve in the FSR. We measured the angle between the inferior endplate of the cranial vertebra and the superior endplate of the caudal vertebra in the FSR, PPR and the MRI.

The FFI below the main curve was defined as the intervertebral space caudal of the main curve of the deformity that opened to different sides in the PPR (Fig. 2). We measured the angle between the inferior endplate of the cranial vertebra of this intervertebral space and the superior endplate of the caudal vertebra in the FSR, PPR and the MRI.

Statistical analysis was performed by SPSS® 25 (IBM, Armonk, USA). Descriptive data is given as mean and standard error of mean (SEM). We tested all continuous variables for normal distribution by Kolmogorov–Smirnov tests. All variables showed normal distribution. Thus, we assessed correlation by Pearson's correlation index.

For the analysis of the PPR, we always analyzed the angles of the PPR to the concavity of the main curve: In curves with a right convexity, we analyzed the according

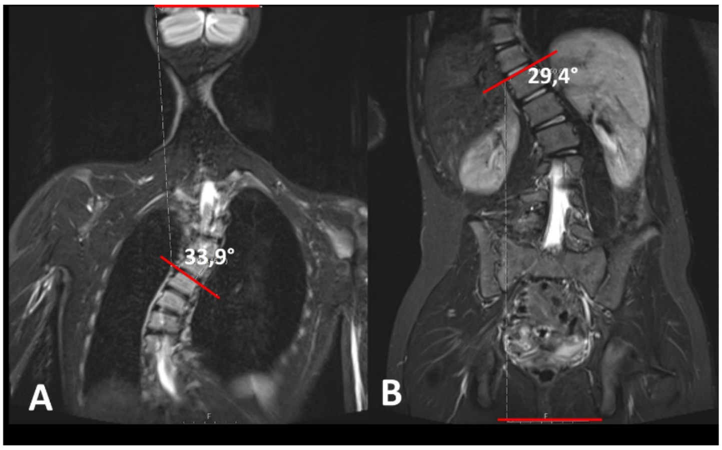

Fig. 1 Measurement of Cobb Angle in a MRI. **A** Coronal reconstruction of a MRI scan of the spine (T2 weighed). The superior endplate of the cranial end vertebra of the according curve is depicted. End vertebra were identified in the FSR. The angle between the superior endplate of the cranial end vertebra and the horizontal plane was 33.9°. **B** Coronal reconstruction of a MRI scan (T2 weighed) of the spine. The inferior endplate of the caudal end vertebra of the according curve is depicted. End vertebra were identified in the FSR. The angle between the inferior endplate of the caudal end vertebra and the horizontal plane was measured with 29.4°. Summation of these two angles (33.9 in 1**A**+29.4 in 1**B**) determines a Cobb angle of 63.3 degree for this thoracic curve

PPR to the left and in curves with a left convexity, we analyzed the according PPR to the right.

This study was approved by the local ethics committee (Register number 2020-913) and was conducted according to the revised Declaration of Helsinki.

Results

We identified 35 consecutive patients who were treated operatively for AIS in our institution between 04/2017 and 04/2021 and received a preoperative MRI by diagnostic code. After application of the inclusion and exclusion criteria, we enrolled 25 patients to our investigation. Sixteen patients were female (64%), and nine patients were male (36%). The average age at the date the radiographs were performed was 15.48 (3.30) years. According to the Lenke classification, 18 patients had a type 1 curve, three patients a type 5 curve, two patients type 2 and two patients a type 6 curve.

In Table 1, we present data of the Cobb angle of the main and of the minor curve in the FSR, PPR and the MRI.

In a subgroup analysis of all patients with a minor curve of less than 40° in the FSR (more than 40° characterizes a structural curve), we analyzed the Cobb angles of the minor curve in the PPR and MRI. If the minor curve was less than 30° in the MRI, it was also less than 25° in the PPR in 100% of these patients.

Tables 1, 2, 3 and 4 show values of Cobb angles of the FSR, PPR and the MRI.

There was a significant correlation ($p < 0.05$, Corr Coeff = 0.41) between the Cobb angle of the main curve in FSR and the Cobb angle of the main curve in the MRI.

Furthermore, we found significant correlations between the minor curves in the different types of radiographs. There was a significant correlation ($p < 0.001$, Corr Coeff = 0.04) between the Cobb angle of the minor curve in FSR and the Cobb angle of the minor curve in the MRI.

The difference between the Cobb angle of the main curve in the FSR and in the PPR shows a significant correlation ($p < 0.05$, Corr Coeff = 0.41) to the difference between the Cobb angle of the main curve in the FSR and the Cobb angle of the main curve in the MRI.

The difference between the Cobb angle of the minor curve in the FSR and in the PPR shows a significant correlation ($p < 0.001$, Corr Coeff = 0.9) to the difference between the Cobb angle of the minor curve in the FSR and the Cobb angle of the minor curve in the MRI. There was a significant correlation ($p < 0.05$, Corr Coeff = 0.47) between the difference of the Cobb angle of the ISE in the FSR and in the PPR and the difference of the Cobb angle of the ISE in the FSR and in the MRI.

According to the Cobb angles of the FFI, there were no significant correlations between the different images.

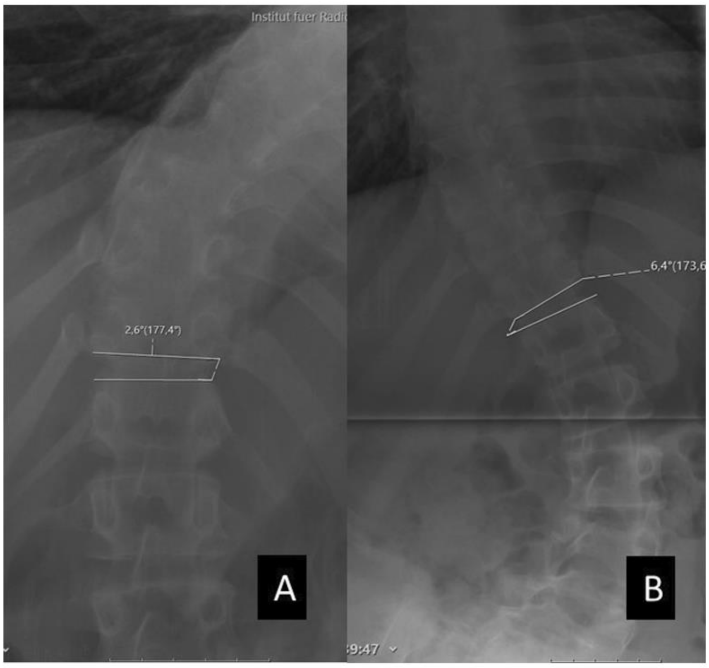

Fig. 2 Identification of the FFI in the PPR—The FFI below the main curve was defined as the intervertebral space caudal of the main curve of the deformity that opened to different sides in the PPR. **A** Part of a PPR of the spine with bending to the left. Zoom is on the caudal end of the main curve. End vertebra were identified in the FSR. Marked is the first intervertebral space below the main curve of the deformity that opens to the concave side with regard to the analyzed curve. The angle between the inferior endplate of the cranial vertebra of this intervertebral space and the superior endplate of the caudal vertebra is measured. **B** Part of a PPR of the spine with bending to the right. Zoom is on the caudal end of the main curve. End vertebra were identified in the FSR. Marked is the first intervertebral space below the main curve of the deformity that opens to the other side than the same intervertebral space in **A**. The angle between the inferior endplate of the cranial vertebra of this intervertebral space and the superior endplate of the caudal vertebra is measured

Table 1 Cobb angle of the main and the minor curve in FSR, PPR and the MRI

	Cobb angle of the main curve in FSR	Cobb angle of the minor curve in FSR	Cobb angle of the main curve in PPR	Cobb angle of the minor curve in PPR	Cobb angle of the main curve in MRI	Cobb angle of the minor curve in MRI
Mean	61.20	42.16	64.32	20.56	64.71	35.06
SEM	2.56	2.45	2.44	2.72	4.30	2.28

Table 2 Cobb angle of the ISE and FFI in FSR, PPR and the MRI

	Cobb angle of the ISE in FSR	Cobb angle of the FFI in FSR	Cobb angle of the ISE in PPR	Cobb angle of the FFI in PPR	Cobb angle of the ISE in MRI	Cobb angle of the FFI in MRI
Mean	5.27	6.70	−3.32	−3.52	2.46	3.76
SEM	0.53	0.62	0.91	0.55	0.62	0.86

Table 3 Difference in the Cobb angle of the main curve and minor curve in FSR and PPR and in the in FSR and the MRI

	Difference in Cobb angle of the main curve in FSR and PPR	Difference in Cobb angle of the minor curve in FSR and PPR	Difference in Cobb angle of the main curve in FSR and MRI	Difference in Cobb angle of the minor curve in FSR and MRI
Mean	26.72	22.31	7.22	7.10
SEM	1.86	2.27	1.87	1.48

Table 4 Difference in the Cobb angle of the ISE and FFI in FSR and PPR and in the FSR and the MRI

	Difference in Cobb angle of the ISE in FSR and PPR	Difference in Cobb angle of the FFI in FSR and PPR	Difference in Cobb angle of the ISE in FSR and MRI	Difference in Cobb angle of the FFI in FSR and MRI
Mean	5.60	10.22	2.81	2.94
SEM	0.80	0.72	0.60	0.68

Discussion

In this study, we found a significant correlation ($p < 0.05$) for all analyzed Cobb angles between BR and MRI.

Brink et al. reported a significant correlation of the morphology of the scoliotic spine in all three planes between standard upright X-ray, MRI and CT scan [14]. Keenan et al. [15] showed 2014 that there is a statistically significant relationship between the Cobb angle in supine and upright position for the major curve. However, minor curves were not analyzed, especially not with regard to the flexibility of the curve. There is presently no data that compares the assessment of flexibility of the minor curve in BR versus MRI scans.

According to the data of this study, it does seem likely that Cobb angles of the main and the minor curves in MRI may provide similar information as a PPB.

Furthermore, our data show that it is possible to determine if a minor curve is structural or non-structural by analyzing the Cobb angle in the MRI. Every patient with a Cobb angle of the minor curve of less than 40° in the FSR and a Cobb angle of the minor curve less than 25° in the PPB showed a Cobb angle of the minor curve in the MRI of less than 30°. These curves are, according to the Lenke classification, non-structural and do not have to be included in the selective spinal fusion [3]. According to this data, in our group of patients a Cobb angle of < 35° in the recumbent MRI scan determined a non-structural curve. This is comparable to the results of a former investigation of our group where we showed that a Cobb angle of the minor curve of less than 35° in the CTS indicated that this minor curve was non-structural [13].

These results may indicate that neither PPR's nor CTS are necessary to determine if a curve is structural or non-structural. This may provide a means for the reduction of the dose of radiation for scoliosis patients and for the medical personal. However, it also has to be taken into account that the costs for performing an MRI instead of plane radiographs are approximately three times higher. Furthermore, it has to be mentioned that MRI's are not equally available in all regions and the waiting time for obtaining an MRI as well as the technique itself takes longer than BR. But since we discuss a technique for an elective surgery without any emergency character, these above-mentioned points should be, in our opinion, considered as minor consequence compared with the fact that exposure to radiation might be reduced.

If some patients might have contraindications against an MRI (e.g., anxiety or a pacemaker), it could be necessary to fall back to the technique with plain radiographs.

Furthermore, we saw that there are significant correlations between the Cobb angles of the ISE in the analyzed radiographs. However, statistical power was rather low, especially in the correlations between the PPR and the MRI. Thus, we presently cannot apply the MRI as a tool to analyze the flexibility of the ISE.

A limitation of our investigation is that we performed a retrospective data analysis. Furthermore, we only analyzed the correlation between the PPR and the MRI and did not investigate other types of BR. However, former analyses showed that PPR are appropriate to determine the effects of a correction of the main curve on the curves above and below the level of fusion by better predicting the translational correction of the lowest instrumented vertebra and the rotation of the lowest instrumented vertebra than other types of BR [16]. The available data show that none of the common types of BR is superior to the others [6, 8, 10, 15, 17, 18].

Conclusion

Cobb angels of push-prone bending radiographs show a significant correlation with Cobb angles in MRI scans. In our group of patients, a Cobb angle of a minor curve in a recumbent MRI scan of less than 30° determined a non-structural curve in 100% of all cases.

Author contributions MP was involved in conception and design, administrative support, collection and assembly of data, provision of study materials or patients, data analysis and interpretation, manuscript writing, final approval of manuscript. MR helped in administrative support, collection and assembly of data, provision of study materials or patients, data analysis and interpretation, manuscript writing, final approval of manuscript. RT contributed to administrative support, collection and assembly of data, provision of study materials or patients, data analysis and interpretation, manuscript writing, final approval of manuscript. JW was involved in administrative support, provision of study materials or patients, manuscript writing, final approval of manuscript. MRK helped in administrative support, collection and assembly of data, provision of study materials or patients, data analysis and interpretation, manuscript writing, final approval of manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

Availability of data and materials The datasets generated during and/or analyzed during the current study are not publicly available due data protection but are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest MP none. MER none. RT none. JW none. MRK reports personal fees from Globus Medical and Depuy Synthes, outside the submitted work. The other authors declare no conflict of interest relevant to this work.

Ethical approval This study was approved by the local ethics committee (Register number 2020-913) and was conducted according to the revised declaration of Helsinki.

Consent to participate Not applicable because of the retrospective design of the investigation.

Consent for publication Not applicable because of the retrospective design of the investigation.

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Prost M, Windolf J, Konieczny MR. Bovine-derived xenograft is a viable bone graft substitute in multilevel, instrumented, spinal fusion. *Orthopedic Reviews*. 2022;14(3). doi:10.52965/001c.37576

General

Bovine-derived xenograft is a viable bone graft substitute in multilevel, instrumented, spinal fusion.

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Keywords: adolescent idiopathic scoliosis, selective spinal fusion, bone-graft, spine surgery, spine deformity

https://doi.org/10.52965/001c.37576

Orthopedic Reviews

Vol. 14, Issue 3, 2022

Objective

To evaluate radiological outcomes following the use of xenogeneic bone graft substitute (BGS) in patients undergoing multisegmental spinal fusion.

Summery of Background Data

Data exists for single level and short segment fusions, there presently is a paucity of data on fusion rate after bone augmentation with BGS in multisegmental posterior spinal fusion (PSF). The leading concern is pseudarthrosis, which often leads to a loss of correction after PSF. Therefore, the bone graft is an essential aspect of PSF.

Methods

We retrospectively analysed the radiological data of a consecutive cohort of patients who had been treated for adolescent idiopathic scoliosis (AIS) via multisegmental spinal fusion, in whom a bovine derived BGS had been used and had a complete dataset of 24 months follow-up. The Cobb angle of the main curve was measured pre-operatively and then at 6, 12 and 24 months post-operatively. Loosening of the screws was recorded at the same post-operative time points.

Results

After applying inclusion and exclusion criteria, 28 patients were included. We found no significant change of the cobb angle from the main curve as well as the cobb angle from the thoracic kyphosis during the 24 months of follow up. No patient showed a lack of bony fusion. There was 1 revision surgery, which was due to trauma.

Conclusion

In this cohort, all patients showed successful bone fusion during a 24-month follow-up. Additionally, there was no change in the Cobb angle during the 2-year post-operative period. Our data indicates that the use of bovine-derived BGS supports bone fusion after multisegmental posterior instrumented fusion of the spine.

INTRODUCTION

Among young people, adolescent idiopathic scoliosis (AIS) is a common cause of spinal deformity. Epidemiologically, AIS is the most common form of scoliosis[1,2] with a reported prevalence of 5.2% in Germany.[3] In the United States alone, it has been estimated that AIS affects more than 4 million people, with approximately 1 million children exhibiting some degree of spinal deformity.[4] In accordance with this epidemiological data, the frequency of spinal fusion has been increasing in some countries.[5]

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While bracing is an effective treatment in some cases,[6] progression to more severe AIS is often treated by posterior spinal fusion (PSF).[5,7] Bony fusion in PSF is usually achieved by dorsolateral decortication and application of autologous iliac crest bone graft (ICBG),[8,9] a technique for which the reported rate of pseudarthrosis is less than 5%.[10,11] However, donor site morbidity is an issue of this technique and is reported to occur in 2% to 45% of all cases.[12,13] This donor site morbidity is why augmentation by bone graft substitutes (BGS) is becoming more popular than the augmentation by ICBG, for example in short segment fusion and treatment of pseudarthrosis.[9,14,15]

While data exists for single level and short segment fusions, there presently is a paucity of data on fusion rate after bone augmentation with BGS in multisegmental PSF. The leading concern is pseudarthrosis, which often leads to a loss of correction after PSF.[16] Therefore, the bone graft is an essential aspect of PSF. As more segments are involved in the PSF, larger amounts of bone graft are needed, and in paediatric cases the supply of ICBG could pose a problem. Therefore, the use of an effective BGS instead of autologous bone grafts would be beneficial, especially in paediatric deformity surgery where large amounts of bone graft are needed for multisegmental PSF, with a subsequent high rate of donor site morbidity.[12,13]

ICBG is considered the gold standard for achieving bony fusion, however the use of BGS to support bony fusion is becoming more common.[17] While BGS is established for use in short-segment posterior spinal instrumentation, there is insufficient data regarding its use in multisegmental spinal fusion. Therefore, this study was conducted to analyse if a natural BGS leads to a fusion rate that would be comparable to that seen with the use of autologous bone graft after PSF for AIS.

METHODS

This was a retrospective review of a prospectively maintained database at our institution. This study was approved by the local ethics committee (Register number 4948) and was conducted according to the revised Declaration of Helsinki. In our clinical documentation system, we identified consecutive patients who were treated operatively for AIS from 02/2008 to 12/2017. We included patients who were treated by selective spinal fusion (SSF),[18] and in whose surgery a bovine-derived apatite BGS (Orthoss® Geistlich Pharma AG, Wolhusen, Switzerland) had been used. We excluded patients with incomplete sets of data or a follow up of less than 24 months. Further we excluded patients with other bone substitute, in order to focus this research question as well as to limit the potential variables. During surgery, the BGS was applied as bone augmentation in a 1:1 ratio with local autologous bone graft that was derived from facet joints, laminotomies and rip hump resections.

BONE GRAFT SUBSTITUTE

The BGS that we used (Orthoss®) is bovine-derived, yet the topography of this substitute is similar to human bone with a high pore connectivity, while the macroporosity of the xenograft is similar to cancellous bone.[19] As a natural hydroxyapatite, there is neither residual organic material nor protein residues, and its potential for bone regeneration has been documented in vitro, via a high permeability to cells and fluids and being rapidly surrounded by new bone without foreign body reaction or encapsulation.[20] These conditions indicate that the BGS is stable over time. Its slow resorption thus makes it valuable for indications where bone volume maintenance is important for long-term stability of the heterotopic bony fusion.[20] Although the clinical use of this material has been documented as early as 1991,[21] the published literature concerning its application in the spine has been limited, with 1 recent paper noting successful outcomes when the material had been used in treatment of vertebral trauma.[22]

Table 1. The demographic data from the patients in our study.

Patients (n)	28
Female	22
Male	6
Age (years)	19.9 ± 10
Segments (n)	8.8 ± 1.9
Time of surgery (minutes)	313 ± 97

OUTCOME MEASURES

Using full spine radiographs (FSR), we measured the Cobb angle of the main and the minor curve as well as the preoperative thoracic kyphosis (TK). These were done directly post-operative, and then at 6, 12 and 24 months postoperative. In these FSR, we measured the Cobb angle of the instrumented main curve and, if applicable, the Cobb angle of the instrumented minor curve. Depending on the spinal fusion that was performed, an instrumentation of the minor curve was not performed in all patients. Additionally, we measured the angle of the TK of the instrumented segments of the curve. Radiological signs for screw loosening or breaking were documented, as well as complications such as breaking of rods or revision surgery.

All radiographs were analysed by measuring instruments from the Sectra IDS 7-PACS System (Sectra, Linköping, Sweden). All statistical analyses were performed under R, version 3.6.3, using the coin-package (version 1.3.1) and the asht-package (version 0.9.6).

RESULTS

Using diagnostic codes, we identified 42 patients who had undergone operative treatment for AIS in our institution between 02/2008 and 12/2017. After application of the inclusion and exclusion criteria, 9 patients were excluded because other bone substitutes were applied. Another 5 patients were excluded due to an incomplete follow-up. Therefore, we analysed the data from 28 patients in our investigation. The demographic data is presented in table 1.

Based on the pre-operative FSR, the average Cobb angle of the main curve was 55.39° ± 11.46° while the average

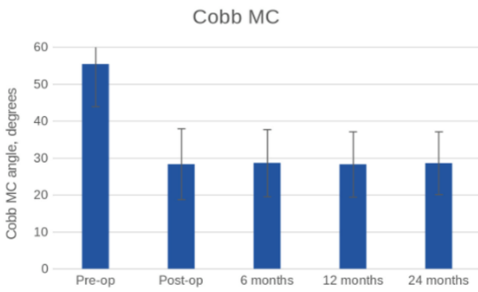

Figure 1. The values of the Cobb angle over time.

Cobb angle of the minor curve was 35.64° ± 12.79°. The average Cobb angle of the instrumented main curve in the FSR directly postoperative was 28.31° ± 9.56°. Thus, there was a correction of the main curve by 27.07° ± 10.94°, or 48.7%.

At 6 months, the average Cobb angle of the instrumented main curve was 28.67° ± 9.06°. At 12 months control the average Cobb angle of the instrumented main curve was 28.29° ± 8.83°while the exam at 24 months showed that the average Cobb angle of the instrumented main curve was 28.6° ± 8.51°. Maximum loss of correction of the Cobb angle of the main curve during the 24 months of follow up was 3°. There were no significant differences of the Cobb angle between any of the post-operative time points, as shown in Figure 1.

There was an average change of the TK of the instrumented segments in the FSR at the 6 months control of 0.35° ± 1.09° while the analysis at the 12 months control revealed an average change of 0.42° ± 1.53° and the 24-month analysis showed a change of 0.64° ± 1.60°. There were no significant differences in this value when compared between any of the post-operative time points

The loosening of one screw was detected in three patients (10.7%) during the 24-month follow-up. In all 3 cases, it was a screw in the lowest instrumented vertebra (LIV) that had loosened. There was no revision surgery needed in 27 cases (96.43%) while there was 1 case (3.57%) of revision surgery due to a rod fracture following trauma (fall from a swing directly on the back).

DISCUSSION

In this consecutive cohort of 28 patients, we noted no significant changes of either the Cobb angle or the TK angles, as measured from immediately post-operative to the 24-month post-operative follow-up. The maximum deviation of the Cobb angle at the end of follow up was 3° for the TK and for the main curve in the frontal plane it was 3°. In addition, we noted 1 screw loosening in each of 3 patients, therefore we consider that the use of the bovine-derived BGS was part of a surgical treatment plan that resulted in a radiographic success rate of 100%.

The role of bone graft remains an important component of PSF, yet the supply of ICBG may remain a limiting factor in choosing the graft material. In adolescents such as we treated, who had not reached skeletal maturity, there is the question of availability of cancellous bone from the iliac crest, a topic which has led to the investigation of alternate grafting materials.[23] A more recent meta-analysis of bone grafts in paediatric patients had also cited bone graft availability as necessitating the consideration of material that could achieve the same goal.[24] The results that we have presented lend credence to the hypothesis that the bovine-derived BGS that we implanted during PSF is capable of maintaining the correction, as evidenced by the lack of change in Cobb angle of thoracic kyphosis. The success rate of 100% compares favourably with the outcomes that had been noted in a large systematic review, in which the fusion rate was reported to be 86.4%.[25] Additionally, our fusion rate was comparable to the recent paper by Weber, *et al.,* (2020) in which the same BGS was used and the authors reported radiographic evidence of fusion in 83% of the levels treated.[22]

We choose an increase of the Cobb angle of 5° as threshold for a relevant progression of the curve during the 24 months of follow-up and as a possible indicator for a missing bonny fusion because of data from other study groups. Pruijs, *et al.* (1994) had reported that the standard deviation of the differences in Cobb angle for repeated measurements of different investigators was 3.2 degrees and for the repeated measurements by one investigator, it was 2.0 degrees.[26] Peterson and Nachemson defined Curve deformity progression >5° as failure of treatment.[27] None of our patients exceeded this threshold. Thus, there was no loss of correction as an indicator for missing bony fusion in any of our patients.

We detected a screw loosening in 3 of our patients. However, every time a screw was diagnosed as loosened, it was a loosening of a screw from the lowest instrumented vertebra. LIV was in the apex of the minor curve in all 3 patients and thus related to inadequate selection of LIV,[28] and not to missing bony fusion, especially since there was no intention to achieve bony fusion below the LIV.

It is known that screw loosening is an indicator for a missing bony fusion.[29]

With regard to other assessments of failure, we had to perform revision surgery in 1 of our patients. However, the patient needed a revision due to trauma that happened between the 12 and 24-month follow-up. As a result of this accident, the trauma the patient suffered a break of one rod. Thus, in our opinion revision surgery in this case could not be used as an indicator for a missing bony fusion.

Our results for multisegmental PSF are comparable with previous data for short segment PSF. For example, Garin, *et al.,* (2016) reported no fusion failures after the use of the same BGS in PSF. However, their patients underwent PSF for an Average of 4 segments.[30] Korovessis, *et al.,* (2005) had also presented comparable results for bony fusion when a coralline BGS was used for a 1 or 2 segment PSF.[9]

While the outcomes that we have reported are generally positive and suggest that this particular BGS can play a role in surgical treatment for AIS, there are limitations to this study. While a notable limitation of our investigation is that we performed a retrospective data analysis, the data that we presented are routinely acquired in all patients and we enrolled consecutive patients, thus it reflects real-world experience. A further limitation may be that we only looked for indirect markers of a missing bony fusion. Examples for indirect markers are the loss of deformity correction in the frontal or sagittal profile, measured by postoperative changes in the Cobb angle of the instrumented regions, radiological signs for screw loosening in the x-ray or an increase of pain.[31,32] These indirect markers have been shown to be effective in identifying a missing bony fusion after a 24 month follow up.[31] As a direct marker, bone fusion can be identified in a CT scan,[33] but use of a CT (in this case for follow-up) would have led to higher doses of radiation for our patients and there is published data indicating that a cumulative, effective dose of radiographs correlates with a higher incidence of breast cancer in scoliosis patients.[34] Therefore, we prefer to limit the use of CT scans in patients with AIS.

CONCLUSION

In our cohort of consecutive patients, we noted a fusion success rate of 100%, as evidenced by the maintenance of the Cobb angle as well as maintenance of the reduced thoracic kyphosis. As well, we noted the loosening of 1 screw in each of 3 patients in the LIV with no other treatment failures. The data indicates that the use of this BGS during PSF can provide an effective adjunct to autologous bone grafts in adolescent patients.

LIST OF ABBREVIATIONS

AIS adolescent idiopathic scoliosis
PSF posterior spinal fusion
ICBG iliac crest bone graft
BGS bone graft substitutes
SSF selective spinal fusion
FSR full spine radiographs
TK thoracic kyphosis
LIV lowest instrumented vertebra

ACKNOWLEDGEMENTS

We would like to acknowledge Dr. Paul Tregouet for his editorial assistance in the preparation of this manuscript and Udo Wittmann from consult ag – statistical services for performing the statistical analysis

FUNDING

The author(s) disclosed no receipt of financial support for the research, authorship, and/or publication of this article

CONFLICTS OF INTEREST/COMPETING INTERESTS

MRK reports personal fees from Globus Medical, outside the submitted work.

The other authors declare no conflict of interest relevant to this work.

AVAILABILITY OF DATA AND MATERIAL (DATA TRANSPARENCY)

The datasets generated during and / or analyzed during the current study are not publicly available due data protection but are available from the corresponding author on reasonable request.

CODE AVAILABILITY (SOFTWARE APPLICATION OR CUSTOM CODE)

Not applicable

AUTHORS' CONTRIBUTIONS

MP: Conception and design, Administrative support, Collection and assembly of data, Provision of study materials or patients, Data analysis and interpretation, Manuscript writing, Final approval of manuscript.

JW: Administrative support, Provision of study materials or patients, Manuscript writing, Final approval of manuscript.

MRK: Conception and design, Administrative support, Provision of study materials or patients, Data analysis and interpretation, Manuscript writing, Final approval of manuscript.

ETHICS APPROVAL

This study was approved by the local ethics committee (Register number 4948) and was conducted according to the revised declaration of Helsinki

CONSENT TO PARTICIPATE

Not applicable because of the retrospective design of the investigation

CONSENT FOR PUBLICATION

Not applicable because of the retrospective design of the investigation

The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication

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European Spine Journal (2021) 30:3490–3497
https://doi.org/10.1007/s00586-021-06945-7

ORIGINAL ARTICLE

May bending radiographs be replaced by recumbent CT scans in patients with adolescent idiopathic scoliosis?

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Received: 9 March 2021 / Revised: 4 July 2021 / Accepted: 22 July 2021 / Published online: 31 July 2021

Abstract

Purpose There is no data that show if it is possible to determine if a curve is structural or non-structural or to assess flexibility of an adolescent idiopathic scoliosis (AIS) by recumbent images like a CT scan (CTS) instead of bending radiographs (BR). We investigated if the results of BR may be compared to those of CTS.

Methods We retrospectively analyzed prospectively collected data of patients with AIS in whom a selective spinal fusion was performed and in whom a CTS, BR, and full spine x-rays were made preoperatively. We measured the Cobb angles of the main and the minor curve in full spine x-ray, BR, and CTS.

Results After applying inclusion and exclusion criteria, 39 patients were included. We found a strong correlation ($r = 0.806$, $p < 0.01$) between the Cobb angle of the main curve in BR and the Cobb angle of the main curve in the CTS and between the Cobb angle of the minor curve in BR and the Cobb angle of the minor curve in the CTS ($r = 0.601$, $p < 0.01$). All patients with a minor curve of less than 25 degrees in the BR had a Cobb angle of less than 35 degrees in the CTS.

Conclusion Spinal curves showed a significant correlation between bending radiographs and recumbent images (CTS). In our group of patients, a Cobb angle of the minor curve of less than 35 degrees in the CTS indicated that this minor curve was non-structural.

Keywords Adolescent idiopathic scoliosis · Bending radiographs · Radiation protection · Selective spinal fusion

Abbreviations

PPR	Push-prone radiographs
PIN	Pedicle screw insertion guided by navigation
CTS	Preoperative CT scan
FSR	Full spine x-ray in posterior–anterior view
ISE	Intervertebral space below the endvertebra of the main curve
FFI	Frist flexible intervertebral space below the main curve
AIS	Adolescent idiopathic scoliosis
LIV	Lowest instrumented vertebra
BR	Bending radiographs
R	Correlation
P	Level of significance

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Introduction

Adolescent idiopathic scoliosis (AIS) is a deformity of the spine with an incidence of 5% [1]. Depending on the degree of the deformity, assessed by the Cobb angle, conservative or operative therapy is recommended [2]. Patients with AIS who need an operative therapy may be treated with a selective spinal fusion. Important for the success of a selective spinal fusion is the discrimination of structural and non-structural curves of the total deformity according to the Lenke-Classification [3, 5] and to choose the appropriate lowest instrumented vertebra (LIV) [3, 4]. To classify a deformity according to the Lenke classification, bending radiographs (BR) of the spine are mandatory. Spinal curves, which can be reduced to less than 25° in a bending radiograph, are classified as "non–structural" [5]. Furthermore, BR allows assessing the possible potential for correction of the deformity by surgery [6, 7]. There are different types of bending radiographs: Push-prone radiographs (PPR) [8], fulcrum bending radiographs [6], supine side-bending radiographs [9], and radiographs with traction under General Anesthesia [10]. All types of BR lead to an additional amount of exposure to radiation for the patient. Push-prone radiographs lead to an additional amount of radiation to the medical personal.

Other study groups [11, 12] showed that cumulative effective dose of standard radiographs, performed for diagnosis and follow-up of scoliosis correlates with incidence of breast cancer in scoliosis patients and with an increasing incidence for infertility. Therefore, it seems to be relevant to evaluate if the flexibility of the spine can be evaluated without BR. Some surgeons perform a preoperative CT scan (CTS), an MRI or an intraoperative recumbent radiograph if AIS is treated by surgery.

CTS are applied either for preoperative planning or as image acquisition for pedicle screw insertion guided by navigation (PIN).

Since these imaging techniques are performed recumbent, the difference between Cobb angles in standing or recumbent position could be evaluated to analyze flexibility.

To our knowledge, there is no data that shows if it is possible to determine if a curve is structural or non-structural by a recumbent imaging technique. If this would be possible BR might not be necessary anymore if, for other reasons, an MRI, a CTS or an intraoperative recumbent radiograph had been performed. This could lead to a reduction of the exposure to radiation for the patient and for the medical personnel.

We conducted this investigation to analyze if Cobb angles measured in CTS of the spine may render similar information on flexibility and type of curves as PPR.

Patients and methods

We retrospectively analyzed prospectively collected data in a single center study. In our clinical documentation system, we identified consecutive patients in whom an operative treatment for AIS was performed from 05/2016 to 01/2020 by diagnostic code. We included patients who were treated by a selective spinal fusion guided by navigation and with image acquisition by preoperative CTS and who had a full spine x-ray in posterior–anterior view (FSR) and BR in the preoperative planning. In our institution PPR are performed as BR. BR were exclusively performed in patients who were treated by surgery, since these additional radiographs would lead to an additional amount of radiation without any change to the conservative therapeutic concept. We excluded patients with incomplete sets of radiological data. We recorded demographic data like sex, age, and date of menarche, as well as the Lenke-Classification of the included patients.

The radiographs were analyzed by the IDS 7-PACS®-System (Sectra, Linköping, Sweden). In all available radiographs (FSR, PPR, and the CTS) the Cobb angle of the main curve and of the upper and lower minor curve was measured. Furthermore, we measured the segmental Cobb angle of the intervertebral space under the lowest vertebra of the main curve (ISE) and the angle of the first flexible intervertebral space below the main curve (FFI). Measurement of Cobb angle in the CTS is demonstrated in (Fig. 1). Measurement was performed in coronal reconstructions of the CT scan. End vertebras were identified in the FSR. The angle between the superior endplate of the cranial end vertebra and the horizontal plane and the angle between the inferior endplate of the caudal end vertebra and the horizontal plane was measured. These two angles were added to obtain the Cobb angle of the according curve (Fig. 1).

Identification and measurement of the ISE and the FFI

The lowest intervertebral space of the main curve was defined as the intervertebral space between the caudal end vertebra of the main curve and the cranial end vertebra of the caudal minor curve in the FSR. We measured the angle

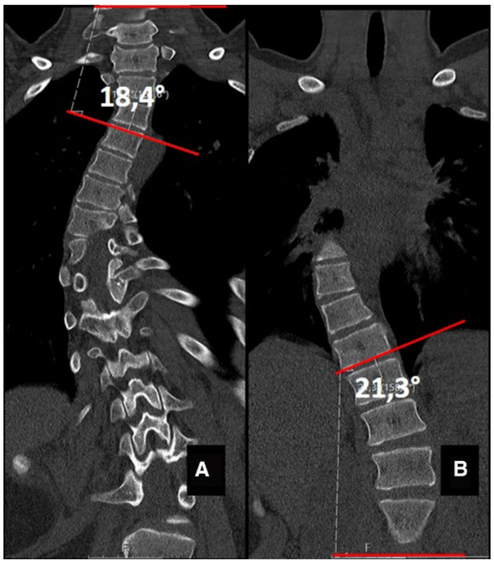

Fig. 1 Measurement of Cobb Angle in a CTS. **a** Coronal reconstruction of a CT scan of the spine. The superior endplate of the cranial end vertebra of the according curve is depicted. End vertebra were identified in the FSR. The angle between the superior endplate of the cranial end vertebra and the horizontal plane was 18,4°. **b** Coronal reconstruction of a CT scan of the spine. The inferior endplate of the caudal end vertebra of the according curve is depicted. End vertebra were identified in the FSR. The angle between the inferior endplate of the caudal end vertebra and the horizontal plane was measured with 21,2 degrees. Summation of these two angles (18,4 + 21,2) gives us a Cobb angle of 39,6 degree for the complete thoracic deformity

between the inferior endplate of the cranial vertebra and the superior endplate of the caudal vertebra in the FSR, PPR, and the CTS.

The FFI below the main curve was defined as the intervertebral space caudal of the main curve of the deformity that opened to both sides in the PPR (Fig. 2). We measured the angle between the inferior endplate of the cranial vertebra of this intervertebral space and the superior endplate of the caudal vertebra in the FSR, PPR, and the CTS.

Statistical analysis was performed by SPSS® 25 (IBM, Armonk, USA). Descriptive data are given as mean and standard error of mean. We tested all continuous variables for normal distribution by Kolmogorov–Smirnov tests. All variables showed normal distribution. Thus, we assessed correlation by Pearsons Correlation Index. Correlation (*R*) and level of significance (p) are reported. The differences of the measured Cobb angles showed significant outliers in the scatterplot and were therefore analyzed by Spearman's rank correlation coefficient.

For the analysis of the PPR, we always analyzed the angles of the PPR against the curve of interest: In curves with a right convexity, we analyzed the according PPR to the left and in curves with a left convexity, we analyzed the according PPR to the right.

This study was approved by the local ethics committee (Register number 2020–896) and was conducted according to the revised Declaration of Helsinki.

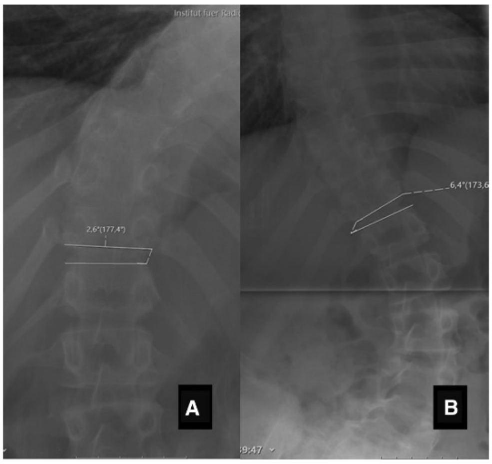

Fig. 2 Identification of the FFI in the PPR. **a** PPR of the spine with Bending to the left. Zoom is on the caudal end of the main curve. End vertebra were identified in the FSR. Marked is the first intervertebral space below the main curve of the deformity that opens to the other side than the same intervertebral space in **b**. The angle between the inferior endplate of the cranial vertebra of this intervertebral space and the superior endplate of the caudal vertebra is measured. **b** PPR of the spine with Bending to the right. Zoom is on the caudal end of the main curve. End vertebra were identified in the FSR. Marked is the first intervertebral space below the main curve of the deformity that opens to the other side than the same intervertebral space in A. The angle between the inferior endplate of the cranial vertebra of this intervertebral space and the superior endplate of the caudal vertebra is measured

Results

We identified 61 patients who were treated operatively for AIS in our institution between 05/2016 and 01/2020 and received a preoperative CT scan by diagnostic code. After application of the inclusion and exclusion criteria, we enrolled 39 patients to our investigation. 28 patients were female (72%), 11 patients were male (28%). The average age at the date the radiographs where performed was 18.23 (8.3) years. According to the Lenke classification 27 Patients had a type 1 curve, seven patients a type 5 curve, three patients type 2 and 2 patients a type 3 curve.

In Table 1, we present data of the Cobb angle of the main and of the minor curve in in the FSR, PPR and the CTS.

In a subgroup analysis of all patients with a minor curve of less than 40 degrees in the FSR (more than 40 degrees characterizes a structural curve) we analyzed the Cobb angles of the minor curve in the PPR and CTS. If the minor curve was less than 25 degrees in the PPR, it was less than 35 degrees in the CTS in 100% of these patients.

Tables 1, 2, 3 and 4 show values of Cobb angles of the FSR, PPR, and the CTS.

There was a strong correlation ($r = 0.746$, $p < 0.01$)) between the Cobb angle of the main curve in FSR and the Cobb angle of the main curve in the CTS. Furthermore, there was a strong correlation ($r = 0.712$, $p < 0.01$) between the Cobb angle of the main curve in FSR and the Cobb angle

Table 1 Cobb angle of the main and the minor curve in FSR, PPR, and the CTS

	Cobb angle of the main curve in FSR	Cobb angle of the minor curve in FSR	Cobb angle of the main curve in PPR	Cobb angle of the minor curve in PPR	Cobb angle of the main curve in CTS	Cobb angle of the minor curve in CTS
Mean	53,28	37,19	30,1053	17,3714	47,0000	34,7059
Standard deviation	9,736	12,269	11,99,051	14,00,648	11,51,497	12,13,692

Table 2 Cobb angle of the ISE and FFI in FSR, PPR, and the CTS

	Cobb angle of the ISE in FSR	Cobb angle of the FFI in FSR	Cobb angle of the ISE in PPR	Cobb angle of the FFI in PPR	Cobb angle of the ISE in CTS	Cobb angle of the FFI in CTS
Mean	428	460	−23,865	−35,737	33,795	36,868
Standard deviation	2578	2812	462,380	293,706	332,718	370,085

Table 3 Difference of the Cobb angle of the main curve and minor curve in FSR and PPR and in the in FSR and the CTS

	Difference in Cobb angle of the main curve in FSR and PPR	Difference in Cobb angle of the minor curve in FSR and PPR	Difference in Cobb angle of the main curve in FSR and CTS	Difference in Cobb angle of the minor curve in FSR and CTS
Mean	240,256	211,974	64,211	35,441
Standard deviation	893,393	1,058,399	776,211	778,924

Table 4 Difference Cobb angle of the ISE and FFI in FSR and PPR and in the FSR and the CTS

	Difference in Cobb angle of the ISE in FSR and PPR	Difference in Cobb angle of the FFI in FSR and PPR	Difference in Cobb angle of the ISE in FSR and CTS	Difference in Cobb angle of the FFI in FSR and CTS
Mean	56,703	81,737	9000	9132
Standard deviation	395,832	337,308	257,294	277,374

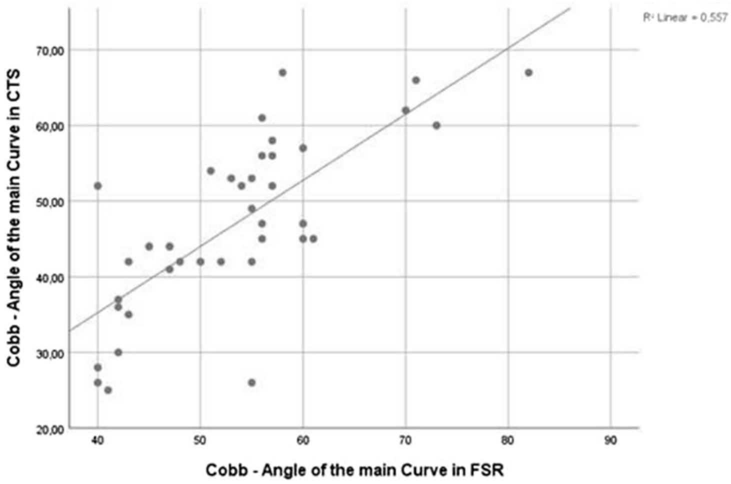

Fig. 3 Correlation between the Cobb angle of the main curve in CTS and FSR. In this scatterplot, the correlation between the Cobb angle of the main curve in CTS and FSR is presented. On the x-axis, the Cobb angle (°) of the of the main curve in the FSR is shown. On the y-axis, the correlated Cobb angle (°) of the of the main curve in the CTS is shown

of the main curve in the PPR. We also found a strong correlation ($r = 0.806$, $p < 0.01$) between the Cobb angle of the main curve in PPR and the Cobb angle of the main curve in the CTS. See also Figs. 3 and 4

Furthermore, we found significant correlations between the minor curves in the different types of radiographs. There was a strong correlation ($r = 0.671$, $p < 0.01$) between the Cobb angle of the minor curve in FSR and the Cobb angle of the minor curve in the PPR. There also was a strong

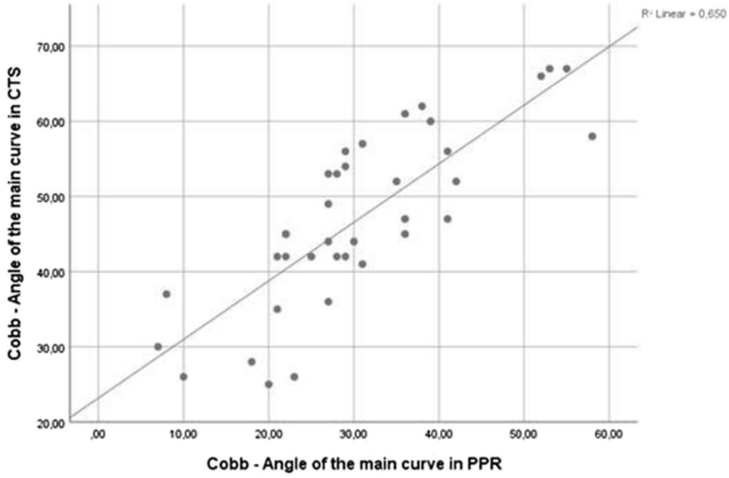

Fig. 4 Correlation between the Cobb angle of the main curve in CTS and PPR. In this scatterplot, the correlation between the Cobb angle of the main curve in CTS and PPR is presented. On the x-axis, the Cobb angle (°) of the of the main curve in the PPR is shown. On the y-axis, the correlated Cobb angle (°) of the of the main curve in the CTS is shown

correlation ($r = 0.802$, $p < 0.01$) between the Cobb angle of the minor curve in FSR and the Cobb angle of the minor curve in the CTS. We also found a strong correlation ($r = 0.601$, $p < 0.01$) between the Cobb angle of the minor curve in PPR and the Cobb angle of the minor curve in the CTS (Figs. 5 and 6).

There was a strong correlation ($r = 0.675$, $p < 0.01$) between the Cobb angle in the ISE in the FSR and in the PPR. There also was a strong correlation ($r = 0.647$, $p < 0.01$) between the Cobb angle in the ISE in the FSR and in the CTS. There was a significant correlation ($r = 0.681$, $p < 0.01$) between the Cobb angle in the ISE in the PPR radiographs and the CTS.

There was no strong correlation ($r = 0.312$, $p > 0.05$) between the Cobb angle in the FFI in the FSR and in the PPR. But there was a strong correlation ($r = 0.668$, $p < 0.01$) between the Cobb angle in the ISE in the FSR and in the CTS. There was a strong correlation ($r = 0.484$, $p < 0.01$) between the Cobb angle in the FFI in the PPR radiographs and the CTS.

The difference between the Cobb angle of the main curve in the FSR and in the PPR shows a strong correlation ($r = 0.424$, $p < 0.01$) to the difference between the Cobb angle of the main curve in the FSR and the Cobb angle of the main curve in the CTS. The difference between the Cobb angle of the minor curve in the FSR and in the PPR shows

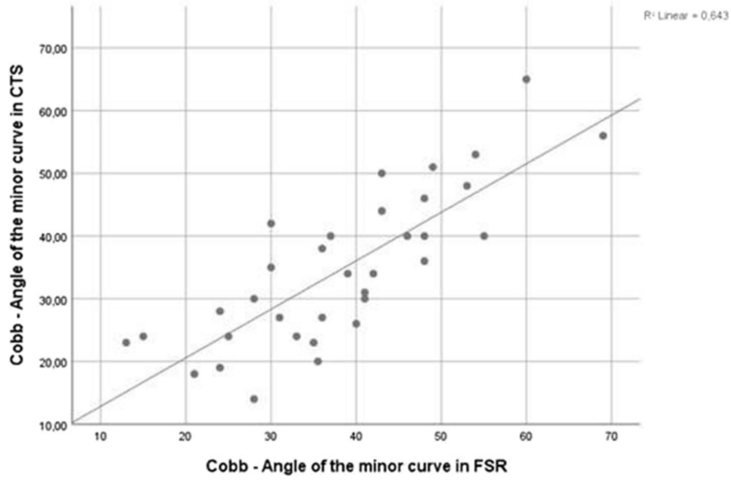

Fig. 5 Correlation between the Cobb angle of the minor curve in FSR and CTS. In this scatterplot, the correlation between the Cobb angle of the minor curve in FSR and CTS is presented. On the x-axis, the Cobb angle (°) of the of the minor curve in the FSR is shown. On the y-axis, the correlated Cobb angle (°) of the of the minor curve in the CTS is shown

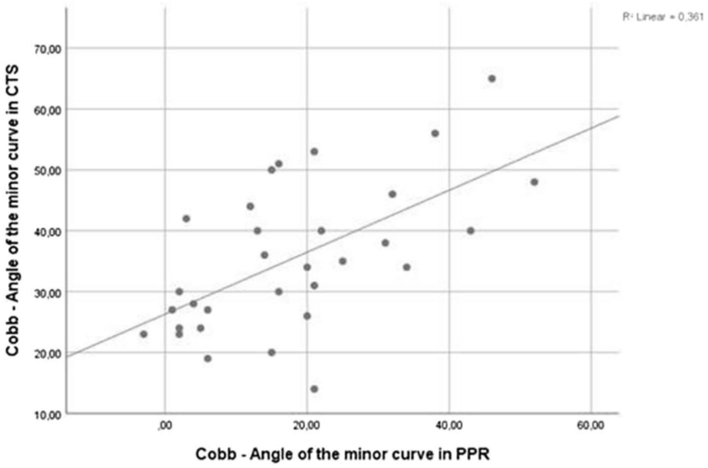

Fig. 6 Correlation between the Cobb angle of the minor curve in PPR and CTS. In this scatterplot, the correlation between the Cobb angle of the minor curve in PPR and CTS is presented. On the x-axis, the Cobb angle (°) of the of the minor curve in the PPR is shown. On the y-axis, the correlated Cobb angle (°) of the of the minor curve in the CTS is shown

a strong correlation ($r = 0.305$, $p < 0.05$) to the difference between the Cobb angle of the minor curve in the FSR and the Cobb angle of the minor curve in the CTS. There was a strong correlation ($r = 0.388$, $p < 0.01$) between the difference of the Cobb angle of the FFI in the FSR and in the PPR and the difference of the Cobb angle of the FFI in the FSR and in the CTS.

Discussion

In this study, we analyzed the FSR, PPR, and the CTS from 39 patients who were treated by surgery for AIS. We analyzed if there are significant correlations in the measured Cobb angles of the main and the minor curves in the FSR, the PPR and the CTS and if there are correlations in the Cobb angles of the ISE and the FFI in the different imaging techniques. We found significant correlation ($p < 0.01$) for all analyzed Cobb angles between BR and CTS.

Brink et al. reported a significant correlation of the morphology of the scoliotic spine in all three planes between standard upright X-ray, MRI, and CT scan [13]. Keenan et al. showed 2014 that there is a statistically significant relationship between the Cobb angle in supine and upright position for the major curve [14]. However, minor curves were not analyzed, especially not regarding to the flexibility. There is presently no data that compares the assessment of flexibility of the minor curve in BR versus CT scans. We therefore conducted this study to analyze if classification of minor curves according to the Lenke classification [3] may be possible by a recumbent CT scan.

In our group of patients, we were able to show, that Cobb angles of the main and the minor curves in the CTS show a significant correlation to Cobb angles in FSR and PPR.

We found a significant correlation of the difference of the Cobb angles of the main and minor curves between FSR and CTS with the difference of the Cobb angles of the main and minor curves between FSR and PPR. This indicates that Cobb angles of the main and the minor curves in CTS may provide similar information as a PPB.

Furthermore, our data show that it is possible to determine if a minor curve is structural or non-structural according to the measured Cobb angle in the CTS. We looked at every patient with a Cobb angle of the minor curve of less than 40 degrees in the FSR and a Cobb angle of the minor curve less than 25 degrees in the PPB. These curves are, according to the Lenke classification, non-structural and do not have to be included in the selective spinal fusion [3]. In this group of patients, the Cobb angle of the minor curve in the CTS was always less than 35 degrees. According to this data, in our group of patients a Cobb angle of < 35° determined a non-structural curve. This indicates that PPR´s are not necessary anymore to determine if a curve is structural or non-structural, if for any reason a preoperative CT scan has been performed. This may lead to a reduction of dose of radiation for the patients and for the medical personal.

Furthermore, we saw that there are significant correlations between the Cobb angles of the ISE and the FFI in the analyzed radiographs. However, statistical power was rather low especially in the correlations between the PPR and the CTS. Thus, we presently cannot apply the CTS as a tool to analyze the flexibility of the ISE and the FFI.

A limitation of our investigation is that we performed a retrospective data analysis. Furthermore, we only performed and analyzed the correlation between the PPR and the CTS and did not investigate the impact of other types of BR. However, former analyses showed that PPR are the most appropriate type of BR to determine the effects of a correction of the main curve on the curves above and below the level of fusion by better predicting the translational correction of the lowest instrumented vertebra and the rotation of the lowest instrumented vertebra than other types of BR [15]. Other investigations detailed characteristics of the different types of BR. Fulcrum bendings are the most appropriate images to assess the maximal preoperative coronal flexibility in main thoracic curves, side-bending radiographs are the most appropriate images to assess the maximal preoperative coronal flexibility in main thoracolumbar or lumbar curves [16]. Radiographs with traction under General Anesthesia lead to a higher degree of correction of severe curves (> 60°). However, it has also been shown that selection of lowest instrumented vertebra based on traction radiographs leads to an increased frequency of decompensation of the non-instrumented lower spinal segments [10, 17]. The available data show that none of the common types of BR is superior to the others [6, 8, 10, 15–17].

The primary objective of this investigation was to analyze if recumbent images could "replace" BR in the diagnostic algorithm of AIS. Since some of our patients were operated by navigation based on a preoperative CTS, we used these CTS images as recumbent imaging technique in this investigation and found that CTS may be applied to classify scoliotic minor curves as structural or non-structural. We presently avoid performing any more pedicle screw insertions guided by navigation (PIN) with preoperative CTS in AIS patients because of the higher exposure to radiation of the patients, but applying navigation by an intraoperative 3D scan [18]. For the same reason, we now aspire to apply different recumbent imaging techniques, i.e., MRI or intraoperative images, as "replacement" for BR. Thus, future investigations should focus on whether other recumbent imaging techniques are as effective as CT scans to classify curve flexibility in scoliosis patients.

Conclusion

Cobb angles of push-prone bending radiographs show a significant correlation with Cobb angles in CT scans. In our group of patients, a Cobb angle of a minor curve in a CT scan of less than 35° determined a non–structural curve in 100% of all cases.

Author's contributions MP involved in conception and design, administrative support, collection and assembly of data, provision of study materials or patients, data analysis and interpretation, manuscript writing, and final approval of manuscript. JW participated in administrative support, provision of study materials or patients, manuscript writing, and final approval of manuscript. MRK involved in conception and design, administrative support, provision of study materials or patients, data analysis and interpretation, manuscript writing, and final approval of manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

Data availability The datasets generated during and / or analyzed during the current study are not publicly available due data protection but are available from the corresponding author on reasonable request.

Declarations

Conflicts of interest MRK reports personal fees from Globus Medical, outside the submitted work. The other authors declare no conflict of interest relevant to this work.

Ethics approval This study was approved by the local ethics committee (registry number 2020–896) and was conducted according to the revised declaration of Helsinki.

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Original Clinical Article

JOURNAL OF CHILDREN'S ORTHOPAEDICS

Effective dose of radiation per screw in surgery of adolescent idiopathic scoliosis: matched pair analysis of 293 pedicle screws inserted using three different techniques

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Abstract

Purpose Reports on heterogenous groups of patients have indicated that pedicle screw insertion guided by navigation (PIN) leads to, for the patient, higher doses of radiation compared with pedicle screw insertion guided by fluoroscopy (PIF). This would be a major concern, especially in paediatric deformity correction.

Methods After a power analysis (aiming at > 0.8) 293 pedicle screws which were inserted in patients with adolescent idiopathic scoliosis were analyzed by comparing effective dose and fluoroscopy time per screw for three different techniques. Groups 2 and 3 were matched to Group 1 by Lenke type of scoliosis. Group 1 were prospectively enrolled consecutive patients that have been operated on by PIN with image acquisition by preoperative CT scan (CTS). Group 2 were consecutive retrospectively matched patients who have been operated on by PIN with image acquisition by an intraoperative 3D scan (3DS). Group 3 were consecutive retrospectively matched patients who have been operated on by PIF.

Results Mean dose of radiation per screw was 1.0 mSv (SD 0.8) per screw in CTS patients, 0.025 mSv (SD 0.001) per screw in 3DS patients and 0.781 mSv (SD 0.12) per screw in PIF patients. The difference was significant ($p < 0.0001$).

Conclusion When we compared different techniques of navigation, navigation by image acquisition with CTS showed a significantly higher (by 97.5%) dose of radiation per screw for the patient than navigation by image acquisition by a 3DS. Navigation by 3DS showed significantly lower effective dose per screw for the adolescent patients than the fluoroscopic technique.

Level of Evidence: II

Cite this article: Konieczny MR, Boos J, Steuwe A, Schleich C, Prost M, Krauspe R. Effective dose of radiation per screw in surgery of adolescent idiopathic scoliosis: matched pair analysis of 293 pedicle screws inserted using three different techniques. *J Child Orthop* 2020;14: 554-561. DOI: 10.1302/1863-2548.14.200148

Keywords: adolescent idiopathic scoliosis; navigation; computer-assisted surgery; effective dose; pedicle screws

Introduction

Pedicle screw insertion guided by navigation (PIN) has been reported to be superior to pedicle screw insertion guided by fluoroscopy (PIF) with regard to accuracy of pedicle screw insertion. Especially in thoracic vertebrae, where the accuracy of PIN is reported to be up to five times higher than that of PIF.[1-5] Additionally, PIN has been reported to significantly reduce exposure of the surgical team to radiation,[6-8] which is highly relevant, especially for high-volume deformity surgeons.

On the other hand, there are reports of higher overall doses, for the patient, of radiation with PIN *versus* PIF[7,9-12] which is a major concern especially in the surgery of paediatric deformities. Doody et al[13] reported that the incidence of breast cancer correlates with dose of radiation and is significantly higher in scoliosis patients than in the normal population.

However, the former reports which state higher doses of radiation in PIN compared with PIF[7,9-12] investigated mainly short segment fusions and enrolled patients with heterogenous indications for surgery, heterogenous surgical levels and heterogenous techniques including minimally invasive surgery (MIS) and standard open surgery,

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with and without interbody spacers. To the best of our knowledge, there is no data available comparing the dose of radiation of PIN *versus* PIF in instrumented posterior fusion of spinal deformities.

PIN can be performed by different techniques of image acquisition, among them intraoperative 3D scan (3DS) and preoperative CT scan (CTS). We do not know which technique allows for lower exposure to radiation; former investigations recorded radiation exposure in non-comparable units (mGy, mGy*cm, cGy*cm^2, mSv/pt, nSv/pt and others) and compared heterogenous groups of patients[11] which did not lead to sufficient data to compare dose of radiation after 3DS with that of CTS. Furthermore, there are no reports that compare these different techniques of image acquisition for navigation with regard to dose of radiation in surgery of spinal deformities. The complexity of the calculation of dose of radiation to compare 3DS and CTS may be one reason why there are no reports on this comparison:

For CTS the dose of radiation that results from the CTS has to be added to the dose of radiation that results from intraoperative fluoroscopic images by C-arm which are performed to control the position of the inserted screws and the result of the deformity correction. This addition is a complex calculation since radiation exposure of CT scans is recorded as dose-length-product (DLP, mGy*cm) and radiation exposure of fluoroscopy is recorded as dose-area-product (DAP, cGy*cm^2).

For 3DS the DAP that results from the 3DS has to be added to the DAP that results from intraoperative fluoroscopic images by C-arm which are performed to control the position of the inserted screws and the result of the deformity correction.

Since the parameters DAP and DLP cannot be compared (cGy*cm^2 *versus* mGy*cm), they both have to be converted to the effective dose in mSv to allow for comparison of dose of radiation of 3DS with dose of radiation of CTS.

Radiation exposure and conversion factors from DAP or DLP to effective dose are hardware- and body mass index (BMI)-dependent. Therefore, conversion factors have to be adapted to the exposed region (thoracic or lumbar spine), as other investigators have described.[14,15]

There is no report that compares the overall dose of radiation (intra- and preoperative) for the patient by navigation with image acquisition by CTS to the dose of radiation of navigation by image acquisition with a 3DS in spinal deformity surgery.

In this study, we investigated which technique of navigation (image acquisition by CTS or image acquisition by 3DS) exposes adolescent patients undergoing surgical correction of idiopathic scoliosis to higher doses of radiation during the insertion of pedicle screws. Furthermore, we tested the hypothesis that PIN leads to lower doses of radiation for the patient than PIF in patients with idiopathic scoliosis.

Patients and methods

We conducted matched pair analysis of consecutive patients. Sample size was determined by a prior power analysis based on a former investigation;[6] 293 screws were analyzed.

Group A: prospective data collection

We prospectively collected data of ten consecutive patients with adolescent idiopathic scoliosis (AIS) that were operated on in a 12-month period by posterior stabilization with a pedicle screw rod construct and PIN with image acquisition by CTS of the relevant spinal segments (group A). Lenke type of scoliosis,[16] number of screws implanted, level of implantation of screw and time of operation were recorded.

Groups B and C: retrospective data collection

We retrospectively included ten consecutive matched patients who were operated on by PIN with image acquisition by 3DS (group B) and ten consecutive matched patients who were operated on by PIF (intraoperative fluoroscopy without navigation) (group C).

Matching procedure

After inclusion of the ten prospective CTS patients (group A), we identified all patients with AIS that were operated on by posterior stabilization with a pedicle screw rod construct in our institution by diagnostic code. Matching patients were allocated, backwards in order of date of surgery, to CTS patients. The first CTS patient that was operated on was matched with the latest patients (one 3DS and one PIF) of the retrospective database that showed identical Lenke type of scoliosis and fused segments. The matching process was conducted accordingly for the remaining nine CTS patients. Patients with incomplete sets of data, previous spinal surgery, BMI > 25 and spinal anomalies were excluded.

All patients operated on by CTS and 3DS were operated on by the first author (MRK), whilst the patients operated on by PIF were operated on by three different surgeons. All surgeons had at least eight years of experience in surgical correction of spinal deformity.

Imaging and technique of pedicle screw insertion: pre-operative CT (group A)

Preoperative CT scans were acquired with a Somatom Definition Flash CT-scanner (Siemens Healthineers, Forchheim, Germany). The scan range included the thoracic and lumbar spine. Scans were performed at a tube potential of either 100 kV_p or 120 kV_p.

Imaging and technique of pedicle screw insertion: navigation (group A and B)

For CTS and 3DS the same C-arm (Arcadis; Siemens Healthineers, Forchheim, Germany) was used in all cases for intraoperative fluoroscopy, which was exclusively applied to control the position of the pedicle screws and the correction of the deformity in CTS patients and additionally for 3D scan in 3DS patients.

The Navigation System 'Kick' (Brainlab, Munich, Germany) was applied in CTS and 3DS. Reference clamp for spinous process was applied and attached to the segment which was instrumented. Preparation of pedicle and insertion of pedicle screws was performed with navigation. In 3DS the operative team left the operating room during fluoroscopy acquisitions.

Imaging and technique of pedicle screw insertion: fluoroscopy (group C)

For PIF a different C-arm (a flat panel detector, Exposcop 8000; Ziehm Imaging, Nürnberg, Germany) was used. Fluoroscopy was exclusively applied for insertion of the pedicle screws and to control the correction of the deformity. Hence, the operative team did not leave the operating room during these fluoroscopic acquisitions. The pedicle screws were inserted similarly to the technique described by Kim et al.[17] Entry points were exposed and identified, then a cortical breach of approximately 5 mm depth was created. Subsequently, a slightly curved gear shift was used to probe the pedicle. It was pointed laterally at first. When the posterior border of the vertebral body should have been reached, according to the inserted length of the probe, it was taken out, the pedicle was palpated to exclude a soft-tissue breach, and reinserted pointing medially. An anteroposterior fluoroscopic control was then made to ensure correct positioning of the probe before it was inserted into the vertebral body. Following this, the entire created canal was palpated to exclude a soft-tissue breach. After screw insertion fluoroscopic control was performed in two planes (anteroposterior and lateral), three to four segments at the same time were checked.

Instrumentation: navigation (groups A and B)

The 3DS and CTS patients were operated on using the same technique. Caudally three to four segments were instrumented by pedicle screws, and the upper instrumented vertebra (UIV) and the vertebra below the UIP (UIV + 1) were instrumented by pedicle hooks. The other vertebra were instrumented by (lamina -) tapes.

Instrumentation: fluoroscopy (group C)

In PIF patients pedicle screws were used in all instrumented vertebra.

Monitoring of the dose of exposure to radiation and calculation of the effective dose

The doses of exposure to radiation were recorded automatically by the different devices (CT scanner or flat panel detectors) and were monitored for all patients.

For group A, the dose of exposure to radiation was recorded by adding the dose of exposure to radiation of the preoperative CT to that of the intraoperative fluoroscopy. The dose of exposure to radiation of group A was compared with the dose of exposure to radiation of groups B and C.

For this purpose, the overall dose of radiation (addition of pre- and intraoperative dose of radiation) that patients operated on by navigation were exposed to was converted to the effective dose (mSv).

3DS

No direct conversion factor was available for the system used in our study (Arcadis). In spite of similarities in the hardware, a direct application of the conversion factors used by Suzuki et al[14] was not possible, since the tube potential for their phantom acquisitions was considerably lower (72 kV_p to 79 kV_p, depending on phantom size). For each patient's image acquisition, the effective dose was calculated by multiplication of the examination's DAP with the thus determined BMI-specific conversion factor. The conversion factors are 0.19 mSv/Gy·cm^2 for the thoracic spine and 0.21 mSv/Gy·cm^2 for the lumbar spine.

PIF

Effective dose was calculated in the same technique as for 3DS.

Since a different C-arm (Exposcop 8000) (which might have led to different doses of radiation for comparable images) was used for PIF patients, we additionally compared time of fluoroscopy of these patients with time of fluoroscopy of 3DS patients to enhance the validity of the results.

CTS

For CT examinations, the International Commission on Radiological Protection (ICRP)103 conversion factors from DLP to effective dose for scans of thoracic and lumbar spine were taken from the recent publication by Huda et al.[18] The conversion factors are 0.0204 mSv/mGy·cm for the thoracic spine (chest region) and 0.0163 mSv/mGy·cm for the lumbar spine (abdominal region).

Effective dose of 3DS and CTS matched patients was compared.

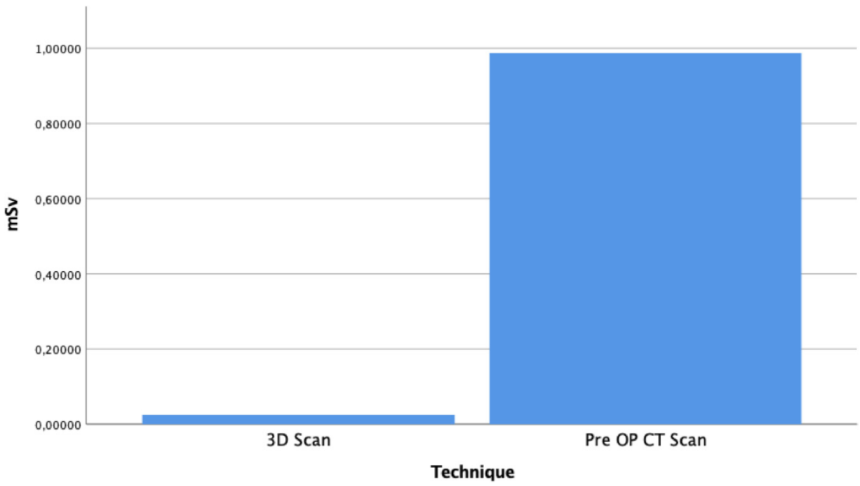

Fig. 1 Effective dose of radiation of pedicle screw insertion guided by navigation. Image acquisition by intraoperative 3D scan *versus* image acquisition by preoperative CT scan.

Statistical analysis

In a matched pair analysis, we investigated if PIN (3DS) was different in CTS, 3DS and PIF with regard to overall dose of exposure to radiation (for the patient). Since dose and time of exposure to radiation did not show normal distribution in a Kolmogorow-Smirnow test, we performed Mann-Whitney U Tests. We first determined which technique of navigation (3DS or CTS) led to the lowest dose of exposure to radiation per screw and then compared this technique with PIF.

Power analysis was performed by G-Power (Heinrich Heine University, Institute for industrial and cognitive psychology, Düsseldorf, Germany)[19,20] based on results of former reports.[6] To achieve a high statistical power (> 0.8) at least 80 screws per group were needed.

Since cancer induction and radiation induced hereditary effects are stochastic effects, there is no 'minimal clinically important difference'; we, therefore, reported the statistical power of our tests.

Statistical analysis was performed by SPSS 25 (IBM, Armonk, New York). Descriptive data are reported as mean and SEM.

Results

Patient cohort

The mean age of the CTS patients was 15.9 years (SEM 0.9) (group A); 16.0 years (SEM 1.6) for 3DS patients (group B); and 15.6 years (SEM 0.8) for PIF patients (group C).

Lenke type was 1A in three pairs, 1B in three pairs, 1C in one pair, 2A in one pair, 2B in one pair and 5C in one pair.

In CTS patients, 81 screws were inserted (8.1 screws per patient), 81 screws in 3DS patients (8.1 screws per patient) and 131 in PIF patients (13.1 screws per patient).

Dose of exposure to radiation

Mean dose of exposure to radiation per screw was 1.0 mSv (SEM 0.8) per screw in CTS patients; 0.025 mSv (SEM 0.001) per screw in 3DS patients; and 0.78.1 mSv (SEM 0.12) per screw in PIF patients (Fig. 1).

The difference between CTS and 3DS was significant ($p < 0.0001$) with a high statistical power (0.95).

The difference between 3DS and PIF was significant ($p < 0.001$) with a high statistical power (0.80).

Fluoroscopy time

Mean fluoroscopy time per screw was 15.0 seconds (SEM 0.8) in all patients; 13.5 seconds (SEM 0.3) per screw in 3DS patients; and 24.1 seconds (SEM 1.4) per screw in PIF patients (Fig. 2).

The difference between 3DS and PIF was significant ($p < 0.0001$) with a high statistical power (0.80).

Complications

In the PIF group three malpositioned screws had to be revised within one week of surgery, two due to neurological deficits and one due to radicular pain. No other

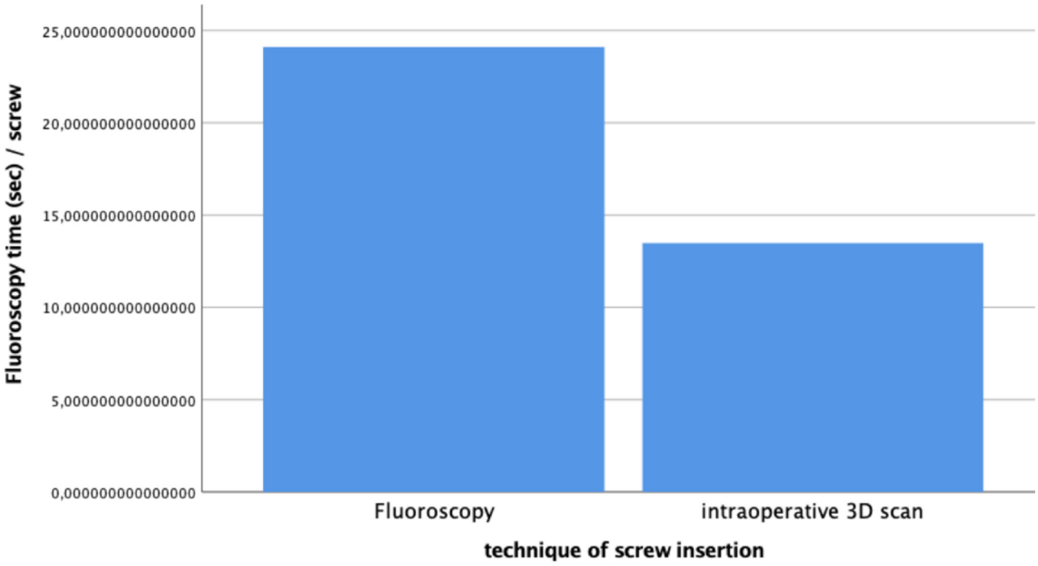

Fig. 2 Effective dose of radiation of pedicle screw insertion guided by fluoroscopy *versus* pedicle screw insertion guided by navigation and image acquisition by intraoperative 3D scan.

complications and no anomalies in the neuromonitoring occurred in all other patients of the three groups.

Discussion

Doody et al[13] showed that cumulative effective dose of standard radiographs, performed for diagnosis and follow-up of scoliosis, correlates with incidence of breast cancer in scoliosis patients. Since PIF and PIN lead to relevant and possible cancer inducing effective doses,[6,21] we should not only focus on the reduction of effective dose by optimizing technique and frequency of standard radiographs for diagnosis and follow-up of scoliosis, but on procedure-related effective dose too. We conducted this investigation to analyze which technique, PIF, 3DS or CTS, leads to the lowest effective dose for the patient. An alternative to PIF (the fluoroscopic technique) is the free hand technique, where the pedicles are felt by probes and ball-tipped guides without radiographic control. Radiation is only applied after the instrumentation to control the screw positions. Usually several levels are controlled simultaneously. This technique leads to a lower effective dose for the patient and for the surgical team than the fluoroscopic technique and also a lower effective dose for the patient than the navigated technique and, if the surgical team leaves the room for the control radiographs, the same reduction of effective dose for the surgical team.

However, Vaccaro et al[1] reported a breaching rate of 40% in the free hand technique. Insertion of PIF shows a breaching rate of 2% to 30% and insertion of PIN shows a breaching rate of 2% to 15%.[2-6] A breaching rate of 0% cannot be achieved by either technique.

Experienced and skilled surgeons might have a lower breaching rate in the free hand technique than less experienced surgeons in the navigated technique. However, statistically, according to available data, the navigated technique shows the lowest breaching rate.

Whether a lower breaching rate justifies a higher procedure-related effective dose cannot be determined. In our opinion it cannot be decided if a higher risk of postoperative pain, neurological deficits and possible revision surgery is 'outweighed' by the stochastical risk for cancer by a higher effective dose or vice versa. However, if PIF or PIN are applied, reduction of the procedure-related effective dose as much as possible is essential.

This investigation showed the lowest effective dose in 3DS. CTS showed a higher effective dose than 3DS and PIF.

There was a reduction of dose of exposure to radiation and fluoroscopy time by 56% (13.5 seconds navigation by 3DS *versus* 24.1 seconds without navigation) when navigation by 3DS was applied compared with the fluoroscopic technique.

There are reports of higher overall doses of radiation by PIN *versus* PIF[7,9-11] in heterogeneous groups of patients.

However, in a previous investigation,[6] we could show that in patients without deformity operated on using a MIS technique without interbody fusion, dose of exposure to radiation of patients was reduced by 41% and for surgeons by 81%.

This result can further be explained by the more difficult insertion of pedicle screws in deformed vertebrae compared with vertebrae without deformity. A former report states that rate of screw accuracy is significantly higher in PIN than in PIF in scoliosis surgery.[22] Depicting a pedicle in the correct plane by fluoroscopy is more challenging in patients with deformity than in patients without deformity and may take more fluoroscopy time.

This part of the study, the comparison of PIF with 3DS, has several possible biases. A different C-arm was used in the retrospective group of PIF patients, thus the comparison of dose of radiation of PIF with 3DS is of lower validity. Less modern image intensifiers might produce images of lesser quality which necessitates more than one image to clarify the position of the implant. However, the fluoroscopy time of 13.5 seconds per screw in 3DS patients *versus* 24.1 seconds per screw in PIF patients seems to indicate that the 3DS technique needed less radiation than the PIF technique.

Furthermore, the PIF patients were operated on by three different surgeons. This might have led to a bias. However, all three surgeons were experienced (at least eight years of experience in deformity surgery) and applied the same technique of pedicle screw insertion in the same institution. Additionally, in PIF all segments were instrumented by pedicle screws, whereas in 3DS and CTS, to reduce effective dose, hooks and tapes were applied for cranial segments, i.e. only one or two 3D scans had to be performed (3DS) or not all segments had to be included in the CTS. This is a possible bias since more challenging pedicles might have been instrumented in PIF than in 3DS and CTS. However, effective dose per screw in 3DS and CTS is the same for all types of pedicles since image acquisition does not dependent on form and shape of the instrumented pedicle, and thus this bias may not be crucial.

These possible biases may render the results of the comparison between the effective dose of PIF with 3DS less valid than the results of the comparison between 3DS and CTS, even if the analysis achieved a high statistical power. In spinal segments with a lower degree of deformity the difference in effective dose between PIF and 3DS might be lower than in spinal segments with a higher degree of deformity. However, the mean effective dose of all spinal segments of PIF was significantly higher than the mean effective dose in 3DS (which is not dependent on degree of deformity), with a high statistical power.

We also compared navigation by CTS with navigation by 3DS. Hecht et al[3] showed that there is no significant difference in accuracy of pedicle screw placement between CT-based navigation and 3D scan-based navigation, which is why we did not analyze accuracy of screw placement. CTS led to a 97.5% higher dose of exposure to radiation (1.0 mSv per screw in CTS *versus* 0.025 mSv per screw in 3DS) than 3DS. This might be due to the larger field of view in a CT scan compared with a 3DS and to the higher resolution of the CT scan compared with a 3DS. The 3D scan can be performed with a lower resolution than the CTS because the registration of the intraoperative images can be performed automatically (a reference clamp is placed before the 3D scan; after the scan the reference is already registered in relation to the images). The CTSs have to be registered intraoperatively by a matching process that requires a higher resolution.

The substantial advantage of CTS is that the CTS allows for meticulous preoperative planning, which is known to reduce the rate of wrong level surgery.[23] However, the results of this study suggest that a CTS before a surgical correction of a pediatric deformity should not be performed, especially since Miglioretti et al[21] showed that an effective dose of > 20 mSv was delivered in 6% to 14% of all spine CTs and that 270 to 800 spine CTs lead to one case of solid cancer.

For 3DS and CTS, the entirety of the operative team was not exposed to radiation since they could leave the operating room during fluoroscopic acquisitions. This seems even more valuable in the light of the report of Rampersaud et al[24] which states that spine surgeons are exposed to up to 12-fold higher dose rates of radiation than other non-spinal musculoskeletal surgeons.

With the fluoroscopic technique the surgical team could, theoretically, also leave the room for each fluoroscopic control, but it would be more often than in the 3DS technique. The plane of the fluoroscopic control often needs to be adjusted, in both planes, to gain acceptable visibility of the pedicle, so the surgeon may need to reenter the room more than once to guide the adjustment. This procedure (leaving and reentering the room) takes time and disturbs the flow of the surgery.

If the surgical team stayed in the room and stepped behind a lead panel, the surgical team must, according to the federal office for radiation protection, still wear lead due to scattered radiation, although eyes and hands would still be unprotected. Even if the resulting procedure-related effective dose to the surgical team would be very low, it would not be 0. The surgeon and the other members of the surgical team might choose to take this risk of exposing themselves to a minimal amount of scattered radiation.

Conclusion

When we compared different techniques of navigation, navigation by image acquisition with CTS of the levels to be instrumented showed a significantly higher (by 97.5%) dose of radiation per screw for the patient than navigation by image acquisition by a 3DS. Navigation by 3DS in posterior instrumented fusion of idiopathic scoliosis showed a significantly lower dose of radiation and fluoroscopy time (by > 50%) per screw for the adolescent patients than the fluoroscopic technique.

Received 1 July 2020; accepted after revision 3 November 2020.

COMPLIANCE WITH ETHICAL STANDARDS

FUNDING STATEMENT

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

ETHICAL STATEMENT

Ethical approval: This study was approved by the local ethics committee (registry number 2018-316-RetroDEuA) and was conducted according to the revised declaration of Helsinki.

Informed consent: Informed consent was obtained from all individual prospectively included participants in the study.

ICMJE CONFLICT OF INTEREST STATEMENT

MRK reports personal fees from Globus Medical, outside the submitted work.

RK reports personal fees from Corin, Nuvasive and Medacta, outside the submitted work.

The other authors declare no conflict of interest relevant to this work.

AUTHOR CONTRIBUTIONS

MRK: Conception and design, Administrative support, Provision of study materials or patients, Data analysis and interpretation, Manuscript writing, Final approval of manuscript.

JB: Conception and design, Data analysis and interpretation, Manuscript writing, Final approval of manuscript.

AS: Manuscript writing, Final approval of manuscript.

CS: Conception and design, Administrative support, Provision of study materials or patients, Manuscript writing, Final approval of manuscript.

MP: Provision of study materials or patients, Collection and assembly of data, Manuscript writing, Final approval of manuscript.

RK: Administrative support, Provision of study materials or patients, Manuscript writing, Final approval of manuscript.

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Clinical Spine Surgery

The Impact of the lowest instrumented vertebra on the correction of the minor curve during selective fusion in patients with adolescent idiopathic scoliosis

--Manuscript Draft--

Manuscript Number:	CSS-23-398R1
Article Type:	Primary Research
Keywords:	Scoliosis; Lowest Instrumented Vertebra; Selective Fusion; Treatment Strategies
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First Author:	Max Prost
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Manuscript Region of Origin:	GERMANY
Abstract:	Study Design: Retrospective single center data analysis Objective: Aim of this investigation was to give advises for choosing the LIV in selective fusion to reach best correction of minor curve and sagittal profile. Summary of Background Data: Scoliotic curves can be classified as structural or nonstructural. If selective fusion is performed, the nonstructural curves are not instrumented. Choice of the lowest instrumented vertebra (LIV) and the impact of different levels of the LIV on the correction of the minor curve in the frontal profile and on the sagittal balance is under debate. Methods: 47 consecutive patients, treated by posterior instrumented fusion, were included in this retrospective investigation. Impact of the level of the LIV with regard to distance to end vertebra (EV), to the stable vertebra (StV), to the sagittal infliction point (IP) and to the apex of the lumbar lordosis on the correction of the minor curve was analyzed. Results: Distance of LIV to EV was significant with regard to correction of the minor curve if it was more than 5 levels ($p<0.001$). Distance of LIV to StV was significant with regard to correction of the minor curve if it was more than 4 levels ($p<0.01$). Distance of LIV to IP was significant with regard to correction of the minor curve if it was more than 2 levels ($p<0.01$). Conclusion: Choosing a LIV that was more than 2 levels higher or lower than the sagittal infliction point showed a significant higher correction of the minor curve. We therefore recommend to keep that distance when LIV is chosen.

Full Title Page (title; author's full names, degrees, and affiliations; corresponding author's contact info; Conflict of

The Impact of the lowest instrumented vertebra on the correction of the minor curve during selective fusion in patients with adolescent idiopathic scoliosis

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Keywords: Scoliosis, Lowest Instrumented Vertebra, Selective Fusion, Treatment Strategies

Declarations:

Funding
No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article

Conflicts of interest/Competing interests
MP Medtronic
PD none
JW none
MRK Globus Medical, Depuy Synthes
The other authors declare no conflict of interest relevant to this work.

Availability of data and material (data transparency)
The datasets generated during and / or analyzed during the current study are not publicly available due data protection but are available from the corresponding author on reasonable request.

Code availability (software application or custom code)
Not applicable

Authors' contributions
MP: Conception and design, administrative support, Collection and assembly of data, Provision of study materials or patients, Data analysis and interpretation, Manuscript writing, Final approval of manuscript.
PD: Administrative support, Collection and assembly of data, Provision of study materials or patients, Data analysis and interpretation, Manuscript writing, Final approval of manuscript.
JW: Administrative support, Provision of study materials or patients, Manuscript writing, Final approval of manuscript.

MRK: Administrative support, Collection and assembly of data, Provision of study materials or patients, Data analysis and interpretation, Manuscript writing, Final approval of manuscript.

Ethics approval (include appropriate approvals or waivers)
This study was approved by the local ethics committee (Register number 4948) and was conducted according to the revised declaration of Helsinki

Consent to participate (include appropriate statements)
Not applicable because of the retrospective design of the investigation

Consent for publication (include appropriate statements)
Not applicable because of the retrospective design of the investigation

Acknowledgement:
The included patients were treated in different departments of the university hospital Duesseldorf inter alia from 2002 up to 7/2019 in the department for orthopedic surgery (Univ.-Prof. Dr. med. R. Krauspe) and since 8/2019 in the department of Orthopedic and Trauma Surgery (Univ.-Prof. Dr. med. J. Windolf)

Some of the Results published in this work were part of the PhD thesis from Philip Denz. In partial fulfillment of the requirements for a PhD thesis for Philip Denz

The Impact of the lowest instrumented vertebra on the correction of the minor curve during selective fusion in patients with adolescent idiopathic scoliosis

Abstract:

Study Design:

Retrospective single center data analysis

Objective:

Aim of this investigation was to give advises for choosing the LIV in selective fusion to reach best correction of minor curve and sagittal profile.

Summary of Background Data:

Scoliotic curves can be classified as structural or nonstructural. If selective fusion is performed, the nonstructural curves are not instrumented. Choice of the lowest instrumented vertebra (LIV) and the impact of different levels of the LIV on the correction of the minor curve in the frontal profile and on the sagittal balance is under debate.

Methods:

47 consecutive patients, treated by posterior instrumented fusion, were included in this retrospective investigation. Impact of the level of the LIV with regard to distance to end vertebra (EV), to the stable vertebra (StV), to the sagittal infliction point (IP) and to the apex of the lumbar lordosis on the correction of the minor curve was analyzed.

Results:

Distance of LIV to EV was significant with regard to correction of the minor curve if it was more than 5 levels ($p<0.001$). Distance of LIV to StV was significant with regard to correction of the minor curve if it was more than 4 levels ($p<0.01$). Distance of LIV to IP was significant with regard to correction of the minor curve if it was more than 2 levels ($p<0.01$).

Conclusion:

Choosing a LIV that was more than 2 levels higher or lower than the sagittal infliction point showed a significant higher correction of the minor curve. We therefore recommend to keep that distance when LIV is chosen.

1. Introduction

The treatment strategies for adolescent idiopathic scoliosis (AIS) depend on the degree of the deformity which is assessed by the Cobb angle [1,2]. According to the Lenke classification, scoliotic curves can be classified as structural or non – structural. [3, 5] When operative treatment is needed it could be performed as selective or non-selective fusion of the spine. If a selective fusion is performed, the non – structural curves are not instrumented. The discrimination of structural and non-structural curves and to choose the appropriate lowest instrumented vertebra (LIV) is crucial for the success of a selective spinal fusion [3, 4].

Data of other study groups suggest, that a LIV chosen too caudal had a negative impact on spinal mobility as well as on quality of life in patients with AIS treated by selective spinal fusion [6, 7]. A LIV chosen too cranial can lead to adjacent segment degeneration or instability [8, 9, 11, 12].

There is already data, which shows the influence of the level of LIV on the magnitude of correction for the main curves [8, 9]. Suggested parameters in the coronal plane to determine the LIV are the distance between the LIV and the end vertebra (EV), the stable vertebra (StV) or the central sacral vertical line (CSVL) [10-12].

However, the debate on how to choose the appropriate LIV with the lowest risk for adjacent segment degeneration or instability on the one hand and maximal spinal mobility for the patient after surgery on the other hand is still ongoing. Especially data on which sagittal parameters should be considered when LIV is chosen is still not conclusive.

This is why we performed a retrospective single center analysis to investigate the influence of different choices of LIV on the correction of the minor curve in selective fusion of patients with adolescent idiopathic scoliosis.

2. Material and Methods

This study was designed as a single center retrospective cohort study. Patients who underwent operative treatment for Scoliosis in our institution between 01/2005 and 01/2020 were identified in the clinical documentation system by diagnostic code.
We included patients who underwent surgical treatment with selective fusion for AIS and who had a complete set of data including full spine x-ray in posterior-anterior and lateral view pre- and post-surgery, as well as during the follow up of at least 24 months. Only patients with Type 1 or 2 curves according to the Lenke classification were included. We excluded patients with any type of previous spinal surgery, other scoliosis forms than AIS, patients with Lenke Type 3, 4, 5 or 6 curves or an incomplete set of data.

Inclusion and exclusion criteria are summed up in **Table 1** *"Inclusion and exclusion criteria"*.

Surgery was performed in all cases with all screws or hybrid (screws and lamina hooks) technique. Both techniques were routinely applied in our institution, and we chose to end data collection when we, in 2020, chose to apply another pedicle screw rod system (manufactured by another company). The principles of deformity correction and the main techniques did, due to the continuous and unchanged leadership of the surgical team of the same person, did not change during the timeframe we applied.
However, choice of LIV was in the discretion of the surgeon.
We recorded demographical data like sex and age, and recorded the Lenke-classification of the included patients.
The radiographs were analyzed by the IDS 7-PACS®-System (Sectra, Linköping, Sweden). The LIV, EV, StV, the sagittal infliction point (IP) and the apex of the lumbar lordosis were identified in the pre- and postoperative full spine radiographs.
In all available radiographs the cobb angle of the main curve and of the upper and lower minor curve was measured. We declared the main curve as being the curve with the highest Cobb angle, according to the lenke classification. Since we investigated the difference of the angle of the minor curve, regardless of the location of the curve, we did not differentiate between these curves. Furthermore, we measured parameters of the sagittal profile (thoracic kyphosis (TK), lumbar lordosis (LL), pelvic incidence (PI)).
The performed measurements were exemplary shown in **Figure 1-3**.

The impact of the level of the LIV with regard to distance to the EV, to the StV, to the sagittal infliction point (IP) and to the apex of the lumbar lordosis on the correction of the minor curve was analyzed.

Statistical analysis was performed by SPSS 25 (IBM, Armonk, USA). Descriptive data are given as mean and standard error of mean (SEM). We tested all continuous variables for normal distribution by Kolmogorov–Smirnov tests. All variables showed normal distribution. Thus, we performed one-way ANOVA analysis and T-Tests.

This study was approved by the local ethics committee (Register number 4948) and was conducted according to the revised Declaration of Helsinki.

3. Results

We identified 241 consecutive patients who were treated operatively for scoliosis in our institution between 01/2005 and 01/2020 by diagnostic code. After application of the inclusion and exclusion criteria, we enrolled 47 patients to our investigation. 39 patients were female (82.9 %), 8 patients were male (17.1 %). The average age at the date the time of surgery was 14.5 (1.14) years. 38 patients (80.1 %) were treated in hybrid and 9 patients (19.9 %) in all screw technique.

The Lenke-Classification of the included patients is shown in **Table 2** *"Lenke-Classification of the included patients"*

The cobb-angles of the main and minor curve in the pre- and postoperative x-rays as well as the achieved correction of the curves are shown in **Table 3** *"Cobb-angles of the main and minor curve in the pre- and postoperative x-rays and the perioperative achieved correction of the curves"*

The mean number of instrumented vertebral bodies was 9.26 (2.60) for all patients, for the patients with Lenke Type 1 curves it was 9.00 and for the patients with Lenke type 2 curves it was 9.50.

The distribution of the LIV for patients with type 1 and type 2 lenke curves is shown in **Table 4 and 5.**

The average distance between the LIV and the EV was 1.91 (1.72) vertebral body's and between the LIV and the StV 1.83 (1.49) vertebral bodies. The average cobb angle of the TK was 25.5° (2.1) pre-op. In the sagittal profile the mean distance between the LIV and the IP of the LL was 1.92 (1.28) vertebral bodies and between the LIV and the apex of the LL 2.14 (1.39) vertebral bodies. The difference of the pre-operative TK to the postoperative TK was 1.9° (1.8).

The difference between the LL and PI pre and postoperative is shown in **Table 6** ***"****Difference between the LL and PI pre and postoperative"*.

Distance of LIV to EW was only significant with regard to correction of the minor curve if it was more than 5 levels (i.e. vertebral bodies) ($p<0.001$). Distance of LIV to StV was only significant with regard to correction of the minor curve if it was more than 4 levels (i.e. vertebral bodies) ($p<0.01$).

The influence from the distance between the LIV and IP on the perioperative correction of the minor curve is shown in **Table 7** ***"Correction of the minor curve depending on the distance between LIV and IP".***

Distance of LIV to IP was significant with regard to correction of the minor curve if it was more than 2 levels (i.e. vertebral bodies) ($p<0.01$). The correlation between the distance of LIV to IP and the correction of the minor curve is high (0.693).

An example for this difference in the achieved correction is shown in **Figure 4**

Further there was a high (0.701) correlation between the perioperative achieved correction of the major curve and the compensatory achieved correction of the minor curve.

Distance of LIV to the apex of the lumbar lordosis was not significant with regard to correction of the minor curve (i.e. vertebral bodies) ($p>0.05$). These parameters did not change during the follow up of 37.6 (5.4) months. No patient required revision surgery.

4. Discussion

In this investigation, we analyzed the data of 47 patients to investigate the influence of the LIV on the correction of the minor curve and the sagittal balance during selective fusion in patients with adolescent idiopathic scoliosis.

The demographical data of our group of patients with an average age of 14.5 years and a female predominance as well as the average preoperative cobb angles and curve types are comparable to the data that are reported in other recent investigations [6-12]. This confirms that our study population is representative.

According to the distance of LIV to EV we found only significant correlation with regard to correction of the not instrumented minor curve if it was more than 5 levels (i.e. vertebral bodies) ($p<0.001$). Other investigations that analyzed the EV as a potential marker to determine the LIV like Suk et. all in 2003 provided no data on this topic [13]. Thus, according to the results of our study group, the EV should not be used to determine the LIV with regard to correction of the not instrumented minor curve.

As another parameter, we analyzed the distance of LIV to StV. This distance was only significant with regard to correction of the not instrumented minor curve if it was more than 4 levels (i.e. vertebral bodies) ($p<0.01$). This influence of the StV according to correction of the not instrumented minor curve is comparable to data presented by Takahasi et al in 2011 who found the best correction potential for the minor curve when LIV is below the StV [8]. A further problem with EV and StV as marker for the determination of the LIV is that both have poor interobserver reliability, therefore determining the LIV based on the StV and EV can be inconsistent amongst different surgeons thus producing variable results [14]. Liu et al. reported, in their systematic review, that there is no recent literature in which landmarks from the sagittal profile where applied to determine the LIV [10]. In our investigation, we were able to show, that there is a significant correlation between the distance of LIV to the IP with regard to correction of the minor curve if it was more than 2 levels (i.e. vertebral bodies) ($p<0.01$). We therefore recommend to respect this distance when LIV is chosen.

Our data might suggest, that if the LIV is chosen too close to the IP, a loss of correction, and in some cases the possible need for another surgery with elongation of the instrumentation, might be the outcome.

However, the IP is rarely found lower than Th12, in Roussoly types 3 and 4 it could be higher than Th12, thus the application of the results of this investigation would hardly lead to an instrumentation to L3 or L4.

These results, in accordance with the recent literature, seem to support the assumption, that it is very important to analyze the sagittal profile when surgical correction with selective posterior instrumented fusion of AIS is planned.

A limitation of our investigation is that we performed a retrospective data analysis and that there was no official study protocol for the treatment of the patients. However, due to standard operating procedures in our department for the surgical treatment of AIS the treatment of the patients is comparable without an official study protocol.

We analyzed data of 241 consecutive patients and consequently applied predetermined inclusion and exclusion criteria, among which a follow up of 24 months – which is important to estimate long term results - was mandatory. This led to a lower number of patients that were enrolled in our final investigation. However this also led to a high quality of our data, and the reported correlation of 0.7 shows a high statistical power of our analysis.

5. Conclusion

In our group of patients choosing a LIV that was more than 2 levels higher or lower than the sagittal infliction point showed a significant higher correction of the minor curve. We therefore recommend keeping that distance when LIV is chosen. Parameters of the frontal profile did only show an impact that was significant if very large distances (5 or more levels) were compared. These results seem to support the assumption, that the sagittal profile shall also be analyzed when surgical correction of an idiopathic adolescent scoliosis is planned.

6. Appendices

6.1. Literature

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6.2. List of Abbreviations

AIS	Adolescent Idiopathic Skoliosis
LIV	lowest instrumented vertebra
EW	end vertebra
StV	stable vertebra
IP	sagittal infliction point
TK	thoracic kyphosis
LL	lumbar lordosis
PI	pelvic incidence
SEM	standard error of mean
CSVL	Central sacral vertical line

6.3. Figure Legends

Figure 1. Measurement of the cobb angle from the main curve and the upper and lower minor curve in an p.a. full spine radiography.

Figure 2. Measurement of the pelvic incidence in a lateral lumbar spine radiography.

Figure 3. Measurement of parameters from the sagittal profile. **A** – Measurement of the lumbar lordosis between L1 an S1 in a lateral lumbar spine radiography. **B -** Measurement of the thoracic kyphosis between Th 1 an Th 12 as well as between Th 5 and Th 12 in a lateral thoracic spine radiography

Figure 4. Two example cases for the impact of the distance between the LIV and the saggital IP on the correction of the minor curve. In both cases the minor curve could be identified as nonstructural in the bending radiographs **A-D** showing pre- and postoperativ x-ray of a patient were the IP and the LIV are on the same level. In this case a correction of the minor curve from 37° to 25° was achieved. E-F showing pre- and postoperativ x-ray of a patient were a distance of 3 vertebras was between the IP and the LIV. In this case a correction of the minor curve from 48° to 28° was achieved.

6.4. Table Legends

Table 1 Inclusion and exclusion criteria

Table 2 Lenke-Classification of the included patients

Table 3 Cobb-angles of the main and minor curve in the pre- and postoperative x-rays and the perioperative achieved correction of the curves. Main curve is declared as being the curve with the highest Cobb angle, according to the lenke classification.

Table 4 Lowest instrumented vertebra in patients with Lenke Type 1 Curves

Table 5 Lowest instrumented vertebra in patients with Lenke Type 2 Curves

Table 6 Difference between the LL and PI pre and postoperative

Table 7 Correction of the minor curve depending on the distance between LIV and IP

Figures

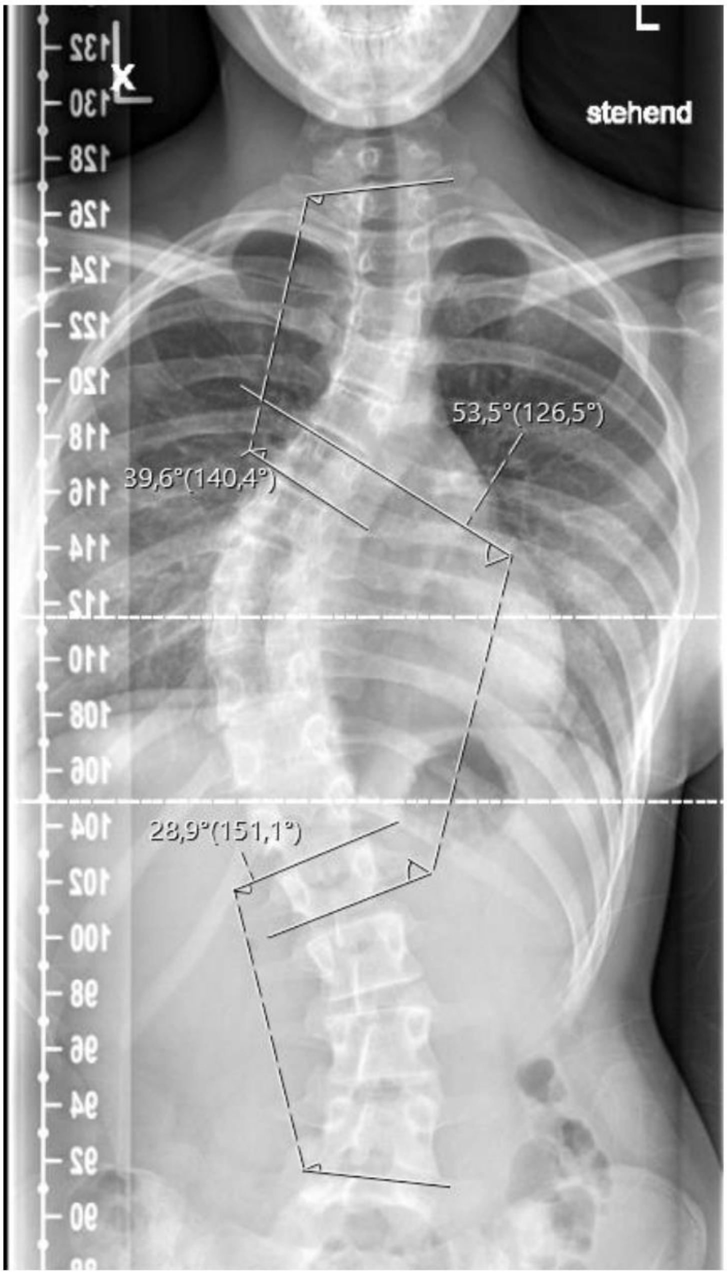

Figure 1. Measurement of the cobb angle from the main curve and the upper and lower minor curve in an p.a. full spine radiography.

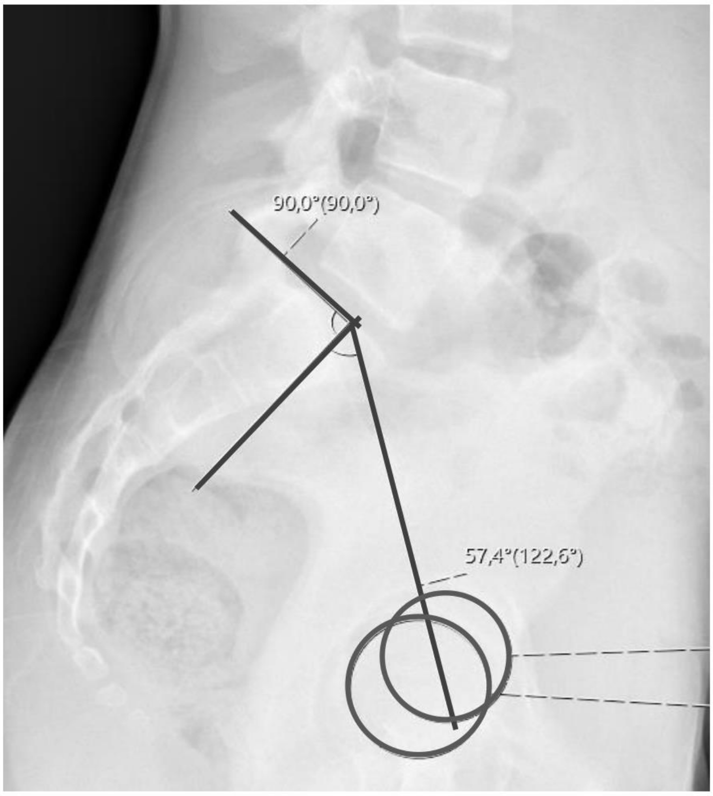

Figure 2. Measurement of the pelvic incidence in a lateral lumbar spine radiography.

Figures

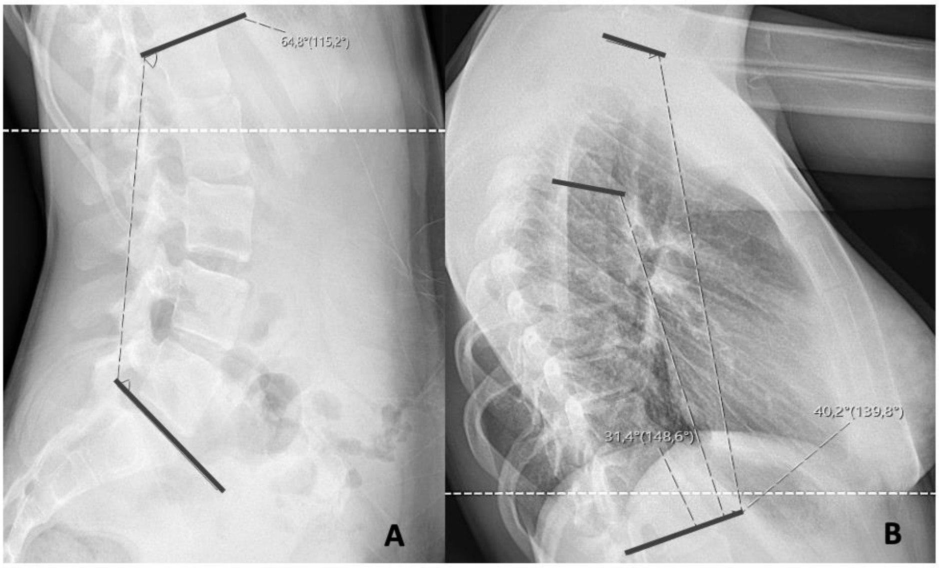

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Figure (1 per file)

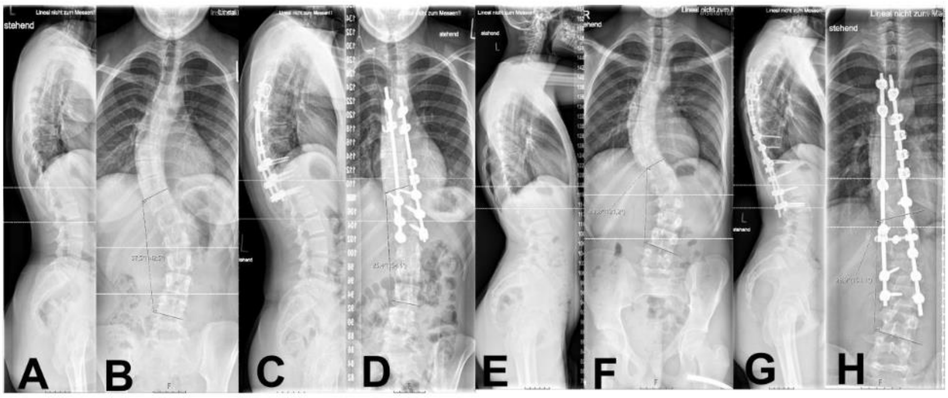

Figure 4. Two example cases for the impact of the distance between the LIV and the saggital IP on the correction of the minor curve. In both cases the minor curve could be identified as nonstructural in the bending radiographs **A-D** showing pre- and postoperativ x-ray of a patient were the IP and the LIV are on the same level. In this case a correction of the minor curve from 37° to 25° was achieved. E-F showing pre- and postoperativ x-ray of a patient were a distance of 3 vertebras was between the IP and the LIV. In this case a correction of the minor curve from 48° to 28° was achieved.

Tables

Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
- Surgical Treatment with selective fusion	- Any type of previous spinal surgery
- Adolescent Idiopathic Scoliosos	- Other Scoliosis Forms (i.e. early-onset or neuromuscular)
- Complete set of data including full spine x-ray in posterior-anterior and lateral view pre- and post-surgery, as well as during the follow up	- Incomplete set of data
- Follow up of at least 24 months	- Patients with Lenke Type 3, 4, 5 and 6 curves
- Patients with Lenke Type 1 and 2 curves	

Table 1 Inclusion and exclusion criteria

Lenke-Classification of the included patients

Type of Curve	Absolute Frequency	Relative Frequency in %
1	23	48.9
2	24	51.1

Table 2 Lenke-Classification of the included patients

	Cobb-Angle Main Curve pre OP	Cobb-Angle Minor Curve pre OP	Cobb-Angle Main Curve post Op	Cobb-Angle Minor Curve post Op	Correction of Cobb-Angle Main Curve	Correction of Cobb-Angle Minor Curve
Mean	57.76	39.23	26.93	21.27	30.83	17.96
SEM	1.83	1.79	1.81	1.53	1.51	1.84

Table 3 Cobb-angles of the main and minor curve in the pre- and postoperative x-rays and the perioperative achieved correction of the curves. Main curve is declared as being the curve with the highest Cobb angle, according to the lenke classification.

Lowest instrumented vertebra in patients with Lenke Type 1 Curves

LIV	Absolute Frequency	Relative Frequency in %
Th 11	3	13.0
Th 12	4	17.4

L 1	6	26.1
L 2	5	21.7
L 3	4	17.4
L 4	1	4.3

Table 4 Lowest instrumented vertebra in patients with Lenke Type 1 Curves

Lowest instrumented vertebra in patients with Lenke Type 2 Curves

LIV	Absolute Frequency	Relative Frequency in %
Th 11	2	8.3
Th 12	6	25.0
L 1	7	29.2
L 2	6	25.0
L 3	3	12.5
L 4	1	4.2

Table 5 Lowest instrumented vertebra in patients with Lenke Type 2 Curves

	LL - PI pre OP	LL - PI post OP	LL - PI: pre – post OP
Mean	7.68	5.10	2.58
SEM	2.12	2.42	2.51

Table 6 Difference between the LL and PI pre and postoperative

Correction of the minor curve depending on the distance between LIV and IP

Distance LIV – IP	Mean correction minor curve in °	SEM
0	13.4	1.4
1	15.4	2.4
2	17.3	3.4
3	24.9	6.7
4	33.7	1.7

Table 7 Correction of the minor curve depending on the distance between LIV and IP