

Selective Thoracic Fusion for King-Moe Type II/Lenke 1C Curve in Adolescent Idiopathic Scoliosis: A Comprehensive Review of Major Concerns

Masayuki Ishikawa¹⁾, Makoto Nishiyama²⁾ and Michihiro Kamata¹⁾

1) Department of Orthopaedic Surgery, Keiyu Hospital, Kanagawa, Japan

2) Spine and Spinal Cord Center, Mita Hospital, International University of Health and Welfare, Tokyo, Japan

Abstract:

Introduction: Controversies still exist in the surgical indications and outcomes of selective thoracic fusion (STF) for a primary thoracic curve with a compensatory large lumbar curve (King-Moe type II/Lenke 1C curve) in adolescent idiopathic scoliosis (AIS). Issues of the greatest concern regarding this curve type include curve criteria that indicate STF to prevent postoperative coronal decompensation and postoperative radiographic outcomes, including curve correction, coronal balance, and thoracolumbar kyphosis, after STF.

Methods: This review comprehensively documents the issues raised in the literature regarding surgical indications and radiographic outcomes of STF for King-Moe type II/Lenke 1C curve in AIS.

Results: Studies suggest that radiographic curve criteria indicating STF for this curve type include the preoperative dominance of the thoracic curve to the lumbar curve in the Cobb angle and the characteristics of the lumbar curve in magnitude and flexibility. Studies warn the need for a careful clinical evaluation of the thoracic and lumbar rotational prominences. Documented radiographic outcomes of importance include the postoperative behavior of the unfused lumbar curve, coronal or sagittal decompensation after STF, and factors associated with these issues.

A comprehensive review of the literature suggests that the use of a segmental pedicle screw construct and better instrumented thoracic curve correction achieve better spontaneous lumbar curve correction. Although the causes of postoperative coronal decompensation remain multifactorial, preoperative coronal decompensation to the left and an inappropriate selection of the lowest instrumented vertebra are consistently reported to be the major causative factors.

Conclusions: STF has been validated in general for the treatment of King-Moe type II or Lenke 1C curve in AIS; however, controversies remain regarding the surgical indications and outcomes.

Long-term impacts of residual lumbar curve, coronal decompensation, and mild thoracolumbar kyphosis on clinical outcomes after STF, along with optimal indications and strategy for STF, should further be assessed.

Keywords:

Adolescent idiopathic scoliosis, King type II curve, Lenke 1C curve, Selective thoracic fusion, Surgical indication, Spontaneous correction, Coronal decompensation, Thoracolumbar kyphosis

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Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity. Surgical intervention is usually indicated if the primary curve exceeds 45°-50° because the long-term natural history of untreated idiopathic scoliosis dictates that such curves progress even after reaching skeletal maturity¹⁻⁴⁾. The untreated, progressed spinal deform-

ity can cause severe trunk deformity, decreased pulmonary function, and disabling low back pain. Surgical intervention with spinal instrumentation and fusion can correct the spinal deformity and achieve the cessation of curve progression, and most studies have shown satisfactory long-term radiographic and clinical outcomes⁵⁻⁸⁾. However, several long-term follow-up studies on postoperative AIS patients have demonstrated that spinal fusion to the middle or lower lumbar

Corresponding author: Masayuki Ishikawa, masa2001@rb4.so-net.ne.jp

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Table 1. Reported Radiographic Criteria of STF for King-Moe II/Lenke 1C Curve.

Author (Year)	Constructs	Criteria
King (1983)	HRI	T Cobb \geq L Cobb, F.I. \geq 0
Lenke (1992)	CDI	T:L Cobb ratio $>$ 1.2, T:L AVT ratio $>$ 1.2, T:L AVR ratio $>$ 1.0, L Cobb $<$ 60°, L AVR $<$ N-M 2.5, L AVT $<$ 4.0 cm
Richards (1992)	CDI, TSRH	L Cobb $<$ 40°
McCall (1992)	CDI	L Cobb $<$ 45°, F.I. $>$ 25
Lenke (2003)	Modern segmental system	T:L Cobb ratio $>$ 1.2, T:L AVT ratio $>$ 1.2, T:L AVR ratio $>$ 1.2, Bending L Cobb $<$ 25°, T10-L2 kyphosis $<$ 10°
Majd (2003)	Modern segmental system	L Flexibility $>$ 50% , Bending L Cobb $<$ 30°
Qiu (2005)	Modern segmental system	T Cobb $>$ L Cobb – 10°, Flexibility L $>$ T, L Cobb \leq 45°, L Flexibility \geq 70%, L AVR $<$ N-M 2, T12-L1 kyphosis \leq 0°
Chang (2014)	PS	Lenke 1234C, Bending L Cobb $<$ 45°, T10-L2 kyphosis $<$ 20°

STF, selective thoracic fusion; HRI, Harrington rod instrumentation; T, thoracic; L, lumbar; F.I., flexibility index; CDI, Cotrel-Dubousset instrumentation; AVT, apical vertebral translation; AVR, apical vertebral rotation; N-M, Nash-Moe; TSRH, Texas Scottish Rite Hospital; PS, pedicle screw

spine may have adverse effects, including an early degeneration of the unfused lumbar spine below the fusion mass with or without low back pain^{4,6,7,9-15}. Therefore, the surgical strategy should aim for maximal three-dimensional spinal deformity correction with a solid arthrodesis while maintaining coronal and sagittal balance, sparing more mobile segments, and avoiding complications. In cases involving significant thoracic and lumbar curves that completely deviate from the midline, whether a selective fusion of the major curve or a fusion of both the thoracic and lumbar curves should be performed remains controversial.

After selective thoracic fusion (STF) for a primary thoracic curve with a compensatory large lumbar curve (now known as a King-Moe type II curve or Lenke 1C curve) was advocated by Moe in 1958¹⁶, numerous reports regarding surgical indications and outcomes of STF for this curve type have been published¹⁷⁻²⁹. While STF is still considered the gold standard for treating this curve type, non-STF, which corrects and fuses both the thoracic and lumbar curves, often necessitating a long spinal fusion to L3 or L4, has also been performed by numerous surgeons³⁰⁻³². Such surgery is undertaken because of the shortcomings of STF, including residual or progressive lumbar curve and coronal or sagittal decompensation after surgery. Thus, several studies on STF for this curve type have focused on radiographic and clinical criteria that make a curve amenable to STF to yield optimal outcomes^{17-29,33,34}.

Radiographic outcomes after STF have been primarily based on the postoperative behavior of the unfused lumbar curve and coronal balance for various surgical approaches or constructs. Spontaneous lumbar curve correction (SLCC), coronal or sagittal decompensation after STF, and their causative factors are major concerns in treating this type of a curve^{18,25-28,35-48}.

With the evolution of spinal implants, devices, and corrective maneuvers and the accumulation of data on the nature of spinal deformity, surgical indications and outcomes of STF have changed. However, the ultimate goals of surgical treatment remain the same, and the efficacy of STF should

be determined by long-term radiographic, cosmetic, and patient-reported outcomes.

This review of the literature aims to increase the surgeons' understanding of our current knowledge of STF with the goal of improving outcomes. Here we comprehensively document the major concerns regarding the use of STF for treating the King-Moe type II/Lenke 1C curve in AIS, including surgical indications and postoperative radiographic outcomes of curve correction, coronal balance, and thoracolumbar kyphosis.

Radiographic Criteria for STF

In 1958, Moe first introduced the concept of STF for a primary thoracic curve with a compensatory lumbar curve and stated that the characteristic of the curve pattern amenable to STF was the primary right thoracic curve with a left lumbar curve, being somewhat structural but not as inflexible as a thoracic curve with bending to the side¹⁶. This concept was a milestone in treating the King-Moe type II/Lenke 1C curve and was subsequently followed by several studies on surgical indications (Table 1). However, clear thresholds on the magnitude or flexibility of curves suitable for STF were not stated in his article.

In 1983, King and Moe advanced Moe's original idea of STF, stating that a King-Moe type II curve, in which both the thoracic and lumbar curves cross the midline and thoracic curve is equal to or larger than a lumbar curve with the flexibility of a lumbar curve being larger than that of a thoracic curve (positive flexibility index), can be successfully treated by STF with the lowest instrumented vertebra (LIV) at the neutral (NV) and stable (SV) vertebra using the Harrington rod instrumentation (HRI)^{17,49,50}. The King-Moe classification of thoracic idiopathic scoliosis was a long-standing, widely accepted system used to classify curve patterns and to recommend fusion levels. However, this system is limited in that the classification is based on the coronal plane only and has relatively poor to fair intra- and inter-observer reliabilities²¹.

In the early 1980's, Cotrel-Dubousset instrumentation (CDI) was introduced in AIS treatment⁵¹. Thereafter, several reports on surgical outcomes of STF using this system for King-Moe type II curve have indicated the significant problem of postoperative coronal decompensation despite the implementation of the King-Moe's rule on LIV selection, leading to the development of several criteria for STF to prevent postoperative coronal decompensation^{18-20,35,37}.

In 1992, Lenke et al. stated that the King-Moe criteria for STF (thoracic curve \geq lumbar curve and positive flexibility index) seemed to work quite well for HRI but were not sufficient when using CDI. This conclusion was drawn on the basis of a retrospective radiographic review of STF for the King-Moe type II curves, including revision cases for postoperative coronal decompensation. More strict criteria for STF with CDI were proposed, including the ratios of the thoracic curve to the lumbar curve in the Cobb angle, apical vertebral translation (AVT), and apical vertebral rotation (AVR). They suggested that 2 or 3 ratios of thoracic to lumbar curves (Cobb angle ratio > 1.2 , AVT ratio > 1.2 , AVR ratio > 1.0) should be fulfilled to obtain successful outcomes after STF; otherwise, postoperative coronal decompensation would be more likely to occur. In addition, curves not meeting the ratio criteria or those with lumbar curves $> 60^\circ$, Nash-Moe's rotation grade > 2.5 , or AVT > 4.0 cm should be treated as a double major curve (non-STF)¹⁸.

In 1992, McCall and Bronson reported the surgical outcomes of STF using CDI for the King-Moe type II curve and determined the causative factors for postoperative coronal decompensation. Based on their evaluation, they provided criteria for STF using CDI, including a lumbar curve of $< 45^\circ$ and a flexibility index of > 25 to prevent postoperative coronal decompensation²⁰.

In 2001, Lenke et al. published the AIS classification system, which combines six coronal curve patterns (1-6) with three lumbar modifiers (A, B, or C) and three sagittal thoracic modifiers (-, N, or +). They stated that STF could be used to treat Lenke 1C curve that meets the following criteria: 1) the main thoracic curve is the major curve (the greatest Cobb magnitude); 2) the thoracolumbar/lumbar curve is a compensatory curve, completely crossing the center sacral vertical line and decreasing to $< 25^\circ$ on side-bending; and 3) thoracolumbar kyphosis (T10-L2) $< 20^\circ$ ^{21,52}. Subsequently, they further speculated that patients with a Lenke 1C curve that meets the thoracic to lumbar curve ratio criteria (Cobb angle ratio > 1.2 , AVT ratio > 1.2 , and AVR ratio > 1.2) with thoracolumbar kyphosis of $< 10^\circ$ are more successfully treated by anterior or posterior STF with a modern segmental system²².

In 2007, Chang et al. showed surgical results of STF using a cantilever bending technique and direct vertebral rotation with pedicle screw (PS) construct for Lenke 1C and 2C curves meeting the Lenke's ratio criteria for STF, in which SLCC exceeds the flexibility of the original preoperative lumbar curve. With the success of this technique for enhancing the capacity of the lumbar curve for spontaneous correc-

tion, they subsequently broadened the indication for STF to all Lenke 1C and 2C curves, regardless of whether they met the Lenke's ratio criteria, and some Lenke 3C and 4C curves in which the preoperative lumbar curves were $< 45^\circ$ on side-bending without thoracolumbar kyphosis of $\geq 20^\circ$ ²⁵⁻²⁸.

In 2014, Schulz et al. published optimal postoperative radiographic coronal parameters after STF for Lenke 1, 2, 3, and 4C curves with queried data, surgeons' opinions, and patients-reported clinical outcomes, including the residual lumbar Cobb angle $< 26^\circ$, lumbar curve correction rate $> 37\%$, coronal balance ≤ 2 cm, trunk shift < 1.5 cm, and a deformity-flexibility quotient (DFQ) < 4 ⁵³. They found that patients with a preoperative lumbar curve $< 45^\circ$ or preoperative bending lumbar Cobb angle $< 25^\circ$ achieve optimal postoperative coronal parameters for the lumbar Cobb angle and DFQ after STF, whereas those with thoracic to lumbar curve ratios > 1.2 in the Cobb angle and AVT do not achieve optimal postoperative coronal parameters²⁹.

Thus, the reported radiographic criteria of STF for this curve type have attempted to optimize the residual unfused lumbar curve size and prevent postoperative coronal decompensation. However, no definite criteria still exist. Further studies to determine more predictable and reproducible criteria for STF using recent three-dimensional imaging techniques are warranted to optimize SLCC and to avoid postoperative coronal decompensation in treating King-Moe type II or Lenke 1C curves.

Table 2 demonstrates the reported incidence of STF and preoperative radiographic measurements of STF vs. non-STF for treating this curve type. A considerable number of patients are still treated with non-STF, despite the original authors' recommendation to use STF for King-Moe type II or Lenke 1C curves. A larger Cobb angle or AVT of a lumbar curve and smaller ratios of the thoracic curve to the lumbar curve in the Cobb angle, AVT and AVR drive a surgeon toward choosing non-STF^{10,31,32,37}.

The original term "STF" describes the fusion of only the thoracic curve in patients with a primary thoracic curve with a compensatory lumbar 'C' modifier curve^{17,22,54}. The majority of reports prefer to define an STF as LIV selected at L1 or above, whereas non-STF is considered to be a long spinal fusion beyond the lumbar apex, with the most common LIV being L3 (Table 2, 3).

Clinical Criteria for STF

King cautioned the importance of the careful clinical evaluation of appearance before surgical intervention, and stated that to be classified as a King-Moe type II curve, the thoracic rotational prominence should be characteristically larger than the lumbar rotational prominence during the forward-bending test^{31,33,34}. Lenke et al. proposed clinical criteria for STF, including 1) right shoulder elevation or leveled shoulders, 2) thoracic trunk shift $>$ lumbar waistline asymmetry, and 3) thoracic to lumbar prominence ratio in scoliometer ≥ 1.2 ²².

Table 2. Reported Incidence of STF and Preoperative Radiographic Measurements of STF vs. Non-STF for King-Moe II/ Lenke 1C Curve.

Author (Year)	Curve type	Institute	N (STF+non-STF)	Parameters	STF	Non-STF	P value
King (1983)	King-Moe II	Multi-center	132	Incidence (%)	84	16	-
				LIV	NA	NA	-
Richards (1994)	King-Moe II	Single-center	35	Incidence (%)	46	54	-
				LIV	NA	NA	-
				L Cobb (°)	46	54	NA
				Bend L Cobb (°)	13	18	NA
				L Flexibility (%)	73	67	NA
Lenke (2002)	Lenke 1C	Multi-center	65	Incidence (%)	62	38	-
				LIV	NA	NA	-
Newton (2003)	Lenke 1B, C	Multi-center	203	Incidence for Lenke 1C (%)	68	32	-
				LIV	≥L1	≤L2	-
				L Cobb (°)	37	42	0.003
				Bend L Cobb (°)	10	13	0.02
				L AVT (mm)	22	31	<0.001
				T/L Cobb ratio	1.44	1.31	0.01
Crawford (2013)	Lenke 1C	Multi-center	264	Incidence (%)	49	51	-
				LIV	≥L1	L3, L4	-
				L Cobb (°)	42.1	47	<0.01
				T AVT (mm)	45.7	39.9	<0.01
				L AVT (mm)	26.1	32.3	<0.01
				T/L Cobb ratio	1.35	1.18	<0.01
				T/L AVT ratio	1.82	1.31	<0.01
				T/L AVR ratio	1.15	0.98	<0.01
Demura (2013)	Lenke 1C	Multi-center	71	Incidence (%)	75	25	-
				LIV	>L1	NA	-
Chang (2014)	Lenke 1C	Single-center	84	Incidence (%)	98	2	-
				LIV	NA	NA	-

STF, selective thoracic fusion; LIV, lowest instrumented vertebra; NA, not available; L, lumbar; AVT, apical vertebral translation; T, thoracic; AVR, apical vertebral rotation

The careful clinical evaluation of the thoracic and lumbar rotational prominences is greater emphasized in thoracic and lumbar curves of comparable Cobb magnitude and AVT on a preoperative postero-anterior radiograph, indicating similar structural characteristics in the thoracic and lumbar curves⁵⁵. One possible reason for the increased rate of non-STF for Lenke 1C curves may be the significant lumbar prominence, implicating a potential limitation of the two-dimensional Lenke's classification³².

Curve Correction

Curve correction rates for instrumented thoracic and unfused lumbar curves after STF for this curve type are reported as 24%-83% and 21%-81%, respectively (Table 3).

In the HRI era, the instrumented thoracic curve correction was approximately equal to or slightly less than the preoperative thoracic curve flexibility on side-bending^{17,34,56-59}. In contrast, thoracic curve correction exceeds preoperative thoracic curve flexibility in modern segmental systems; however, SLCC does not usually exceed the preoperative lumbar

curve flexibility^{7,20,25-28,35,47,48,60-66}. In the CDI era, an overcorrection of the thoracic curve in excess of the preoperative thoracic curve flexibility using a derotation maneuver was considered to be a causative factor of postoperative coronal decompensation. Thus, some reported curve correction rates using this system are somewhat low because of the surgeons' intentional under-correction³⁸⁻⁴⁰. Because the segmental PS construct provides a greater three-dimensional vertebral controllability, several reports of surgical outcomes have demonstrated that a better thoracic curve correction with an appropriate LIV selection results in less postoperative coronal decompensation after STF for this curve type. Thus, the segmental PS construct achieves a better instrumented thoracic curve correction and SLCC with lesser correction loss than HRI or CDI^{25-28,41,44,47,48,64}.

The effect of the approach on SLCC outcomes has also been investigated. Several authors have reported that better SLCC was achieved using anterior STF than using posterior STF with a hook construct, and these studies have speculated that this consequence resulted from surgeons' intentional undercorrection to avoid postoperative coronal decom-

Table 3. Reported Cobb Measurements and Correction Rates in Patients with STF for King-Moe II/Lenke 1C Curve.

Author (Year)	Mean (Min.) follow-up (Year)	Curve type	LIV	Approaches or constructs	N	Thoracic curve (°)				Lumbar curve (°)			
						Pre-op.	Flex. (%)	Final	CR (%)	Pre-op.	Flex. (%)	Final	CR (%)
Shufflebarger (1990)	2.4 (2)	KM II	≥L2	CDI	34	NA	NA	NA	66 [#]	NA	NA	NA	60 [#]
Kalen (1990)	NA (NA)	KM II	NA	HRI, LR, etc.	58	52	33	39	25	32	75	22	31
Bridwell (1991)	1.9 [#] (1)	KM II	NA	CDI	31	53.1 [#]	NA	26.3 [#]	51.2 [#]	38.1 [#]	NA	24.5 [#]	35.3 [#]
Knapp (1992)	3.5 (2)	KM II	SV	HRI	17	58.9	42.4	37.7	37.1	41.1	61.4	27.6	34.6
McCall (1992)	1.6 (0.92)	KM II	≥L1	CDI	23	53.3 [#]	47.7 [#]	NA	NA	40.9 [#]	87.3 [#]	NA	NA
Lenke (1992)	2.7 (0.25)	KM II	≥L1	CDI	27	61	44	35	40	44	70	28	36
Richards (1992)	2 (0.5)	KM II	≥L2	CDI, TSRH	24	61	36	32	48 [#]	49	73	36	27 [#]
Benli (1996)	4.1 (2)	KM II	NA	CDI	12	74.5	NA	56.7 [#]	24 [#]	42.2	NA	25.6 [#]	39 [#]
McCance (1998)	5.5 (2)	KM II	≥L1	HRI, HRI+LR, Hook	67	56.3 [#]	44.9 [#]	34.1 [#]	39.4 [#]	44.3 [#]	78.1 [#]	31.3 [#]	29.3 [#]
Lenke (1999)	2 (2)	MTLC	≥L1	PSF (Hook)	10	67	40 [#]	49	27	53	66 [#]	37	30
				ASF	7	65	34 [#]	27	59	42	71 [#]	21	50
Burton (1999)	4.8 (3.7)	KM IIA	T12*	Hybrid (ISOLA)	6	63	NA	31	51	42	NA	28	33
Frez (2000)	4 (3)	KM II	≥L1	HRI+LR+SPW	24	60.2	37	43.4 [#]	28 [#]	40.7	67 [#]	32.2 [#]	21 [#]
van Rhijn (2002)	6 (2)	KM II	≥L2	HRI+SLW	27	54	46 [#]	31	43	34	85 [#]	22	35
Dobbs (2004)	NA (2)	Lenke 12/C	≥L1	PSF (Hook)	19	62.2	43 [#]	37.5	40	44.4	71 [#]	28.8	36
				ASF	16	62.2	38 [#]	33.2	47	44.8	73 [#]	26.8	41
Edwards (2004)	5 (2)	Lenke 12/C	≥L1	PSF (Hook+Wire/PS)	26	62	NA	42	32	48	NA	32	33
				ASF	15	56	NA	32	43	44	NA	27	39
Suk (2005)	NA (5)	KM II	NA	PS	122	50	51	16	69	33	114	12	62
Dobbs (2006)	3 (2)	MTLC	≥L1	PS	34	62	52	29.4	53	44.6	46	28.4	36 [#]
	4 (2)			Hook	32	61	53	41.1	34	49.5	49	37.5	24 [#]
Chang (2007)	3.5 (2)	Lenke 12/C	≥L1	PS	37	63	35	11	83	47	66	9	81
Patel (2008)	2 (2)	Lenke 1234/BC	≥L1	PSF (Hook, Hybrid)	44	57	44	26	54	40	67	21	49
				ASF	132	53	46	24	55	39	73	22	44
Chang (2010)	6.8 (5)	MTLC	T12, L1	PSF, ASF	32	61.6	41	39.8	36	47.2	61	33.2	25.3
Abel (2011)	3 (2)	Lenke 13/BC	≥L Apex	PSF	123	58.9	NA	26.7	55 [#]	42.2	NA	22.2	47 [#]
Takahashi (2011)	2 (2)	Lenke 1BC/3C	≥L1	PSF (PS, Hook, Hybrid), ASF	93	54	50	23 [#]	58	36	78	19 [#]	46
				SBE	66	51	49	23 [#]	54	39	73	23 [#]	42
				SAE	13	50	57	21 [#]	58	39	72	23 [#]	42
				EBS	13	50	57	21 [#]	58	39	72	23 [#]	42
Wang (2012)	2 (2)	Lenke 1C	≥L1	PS	44	54.4 [#]	39.4 [#]	21.8 [#]	61 [#]	41.7 [#]	75.1 [#]	24.2 [#]	42.5 [#]
Wang (2012)	2 (2)	Lenke 1C	≥L1	PS	29	55.3	NA	22	61	43	NA	25.3	41
Larson (2012)	20.7 (17)	Lenke 1BC/3C	≥L2	CDI, TSRH	14	60	NA	31	48 [#]	44	86	27	38
Yong (2012)	2 (2)	Lenke 1C	≥T12	Thoracoscopic ASF	24	53	59 [#]	24.9	52.5	43.5	74 [#]	25.4	41.8
Ilgenfritz (2013)	5 (5)	Lenke 1C	≥L1	ASF, PSF	24	49	NA	26.5	46	40	NA	24.4	39
Demura (2013)	NA (2)	Lenke 1C	>L1	PSF (PS, Hybrid), ASF	53	49.3	45 [#]	22.3	54.3	39	69 [#]	23.1	40.4
Liljenqvist (2013)	4 (2)	Lenke 12/C	≥L1	ASF (open)	28	61.6	42.9	29.3	52 [#]	47.7	66.2	30.5	36.1 [#]
Chang (2014)	NA (2)	Lenke 12/C	≥L1	PS	150	65	NA	18	72	51	NA	18	65
Schulz (2014)	NA (2)	Lenke 1234/C	≥L1	NA	106	53	40	24	54	41	64	25	40
Enercan (2015)	11.4 (10)	Lenke 1/BC	L1	PS	25	58	43	17	71 [#]	41	63	13	68 [#]
Celestre (2015)	2 (2)	Lenke 1C	≥L1	PSF	38	58.9	NA	28.7	51.3 [#]	45.8	NA	25.5	44.3 [#]
Skaggs (2016)	3.7 (2)	Lenke 1234/C	≥L1	PS	33	60.4 [#]	46.7 [#]	25.2 [#]	57.5 [#]	46.5 [#]	59.6 [#]	26.8 [#]	42.3 [#]
Sullivan (2017)	2 (2)	Lenke 1234/C	≥L1	PSF	121	53	NA	23 [#]	56 [#]	41	NA	23 [#]	43 [#]

STF, selective thoracic fusion; Min., minimum; LIV, lowest instrumented vertebra; Flex., flexibility; CR, correction rate; KM II, King-Moe II; CDI, Cotrel-Dubousset instrumentation; NA, not available; HRI, Harrington rod instrumentation; LR, Luque rod; SV, stable vertebra; TSRH, Texas Scottish Rite Hospital; MTLC, major thoracic-lumbar C modifier curves; PSF, posterior spinal fusion; ASF, anterior spinal fusion; SPW, spinous process wiring; SLW, sublaminar wiring; PS, pedicle screw; L, lumbar; SBE, stable vertebra below end vertebra; SAE, stable vertebra at end vertebra; EBS, end vertebra below stable vertebra; *, mean level; #, estimated values with provided data

compensation when using the posterior approach^{38,39}. Others have reported that anterior and posterior STF with a hook or hybrid construct have similar SLCC in matched cohorts, with respect to the LIV distribution, thoracic curve correction

rate, and preoperative lumbar curve flexibility^{40,42,67-69}.

In most successful cases after STF, the unfused lumbar curve shows significant improvement and accommodates to the corrected thoracic curve, resulting in a balanced spine

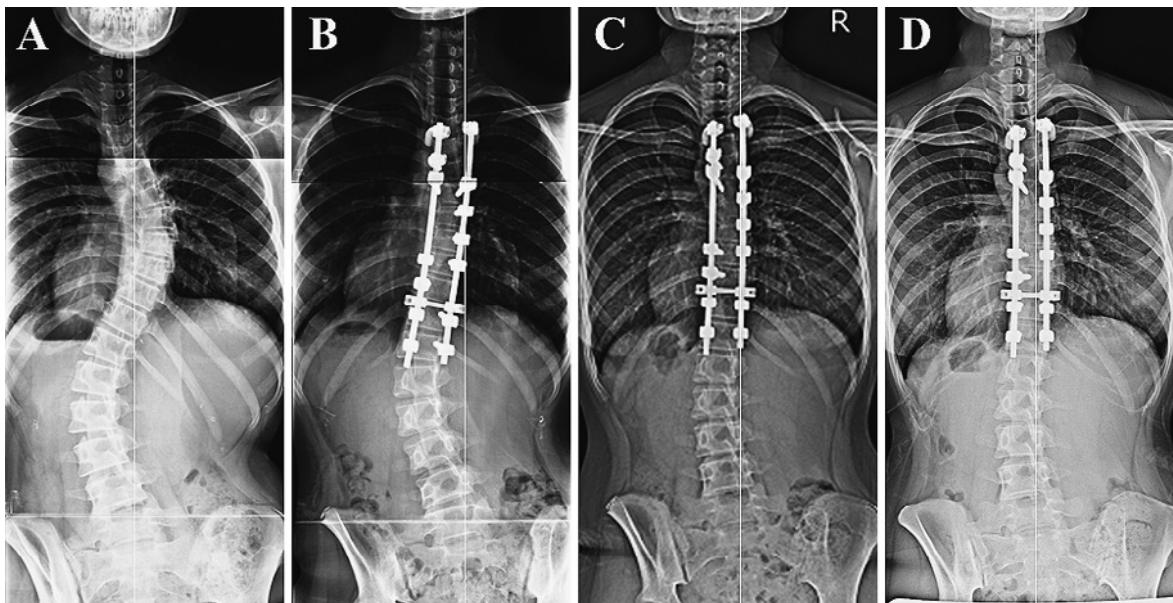


Figure 1. Representative case of a 12-year-old female adolescent idiopathic scoliosis patient with a King-Moe II/Lenke 1CN curve. (A) Preoperative radiograph. (B) Posterior selective thoracic fusion from T4 to T12. Immediately after surgery, the thoracic curve was corrected from 52° to 13° and the lumbar curve was corrected from 44° to 32°, along with coronal decompensation and trunk shift to the left. (C) While the thoracic curve remained stable thereafter, the lumbar curve continued to spontaneously improve at 6 months after surgery. (D) Remodeling of coronal balance and trunk shift was achieved with successful spontaneous lumbar curve correction (17°) and settling of the lumbosacral curve at 6 years after surgery. (A) and (B), with permission to reprint from Elsevier.

and improved lumbar AVT. However, several studies have found that even with successful postoperative courses, lumbar AVR gains only limited improvement after surgery^{22,25-27,39,40,60,65,69-73}. In contrast, if the unfused lumbar curve cannot accommodate to the corrected thoracic curve, then postoperative coronal decompensation with residual lumbar AVT is likely⁷⁴⁻⁷⁹. A possible explanation for this phenomenon, excluding the postoperative curve progression, is that most SLCC occurs above the lumbar apex immediately after surgery because L4 obliquity and lumbosacral curve persist after surgery^{19,39,75-78}. With continued persistence, postoperative coronal decompensation also remains. In successful cases, immediate postoperative coronal imbalance can be remodeled through the slight loss of lumbar curve correction above the lumbar apex and/or settling in the lumbosacral curve due to potential compensation existing in the relatively flexible lumbar curve^{19,45,48}. Moreover, SLCC is sometimes dynamic, and the unfused lumbar curve continues to improve slightly from immediately after surgery through the final follow-up^{22,25,26,38,40} (Fig. 1).

Several factors affecting SLCC have been identified, including the preoperative magnitude and flexibility of the lumbar curve, correction of the thoracic curve or LIV tilt, and LIV selection^{25,29,38,40,42,43,47,56,57,65,66,70,80,81}. While still controversial, evidence suggests that better SLCC is associated with better thoracic curve correction and LIV selection distal to the lower end vertebra (EV) of the thoracic curve.

In majority of patients undergoing STF for this curve pattern, both the thoracic and lumbar curves are reported to be

stable after a 2-year follow-up period, regardless of the approach or the construct used^{4,6,22,34,39,58,69}. However, skeletal immaturity (Risser grade 0-1; open triradiate cartilage) may cause some curve correction loss in the instrumented thoracic and unfused lumbar curves^{22,39,82,83}.

Compared with radiographic outcomes of non-STF, the instrumented thoracic curve correction is comparable or slightly less in STF. However, lumbar curve correction and coronal balance preservation after surgery are significantly inferior in STF at the expense of sparing more lumbar mobile segments^{31,46,62,73,78,84,85}.

Coronal Balance

In King-Moe type II or Lenke 1C curves, preoperative coronal balance is prone to shift to the left, with an incidence of coronal decompensation of 10%-40%^{34,46,48,86}, whereas the incidence of postoperative coronal decompensation after STF is reported to be 2%-75% (Table 4). Although the reported rates of revision surgery for treating postoperative coronal decompensation are very low (Table 4), postoperative coronal imbalance is associated with poor patient-reported outcomes in pain, self-image, function, and satisfaction, as measured on the Scoliosis Research Society questionnaire, indicating its clinical relevance^{22,29,39,87}.

Several causative factors for coronal decompensation after STF have been reported to date (Table 4) and fall under the categories of intrinsic characteristics of spinal deformities, surgical techniques, and LIV selection. Characteristics of

Table 4. Reported Causative Factors, Incidence, and Revision Cases for Postoperative Coronal Decompenation or Trunk Shift after STF for King-Moe II/Lenke 1C Curve.

Author (Year)	Approaches or constructs	CD or TS	Curve type	Causative factors	Incidence (%), (N)	Revision cases
Schufflebarger (1990)	CDI	CD	King-Moe II	hook pattern	NA	NA
Thompson (1990)	CDI	CD	King-Moe II	LIV selection, derotation, overcorrection	75 (9/12)	NA
Mason (1991)	HRI, CDI	TS	PTCL	lumbar angle >15°, L4 tilt >12°, L-AVT>2 cm	HRI; 4 (1/24), CDI; 41 (7/17)	NA
Moore (1991)	CDI	CD	King-Moe II	LIV selection, derotaion	NA	NA
Bridwell (1991)	CDI	CD	King-Moe II	derotation, overcorrection, hook pattern, rod contour	29 (9/31)	3
Lenke (1992)	CDI	CD	King-Moe II	smaller T/L ratio, derotation	16 (3/19)	3
McCall (1992)	CDI	CD	King-Moe II	L Cobb>45°, F.I.<25, overcorrection	17 (4/23)	NA
Richards (1992)	CDI, TSRH	TS	King-Moe II	L Cobb>40°, persistant L4 obliquity	NA	NA
King (1994)	HRI, CDI, ISOLA	CD	King-Moe II	LIV selection, derotation	NA	NA
Benli (1996)	CDI	CD	King-Moe II	L Cobb>40°, overcorrection	NA	NA
McCance (1998)	HRI, HRI+Luque, Hook	CD	King-Moe II	LIV selection, large Cobb (T, L)	30 (20/67)	0
Edwards (2004)	PSF (Hook+Wire/PS), ASF	CD	Lenke 1C, 2C	preop. CD	PSF; 46 (12/26), ASF; 53 (8/15)	0
Dobbs (2004)	PSF (Hook), ASF	CD	Lenke 1BC, 2BC	preop. CD, overcorrection	PSF; 9 (4/44), ASF; 2 (1/56)	0
Suk (2005)	PS	CD	King-Moe II	overcorrection	6 (7/122)	0
Dobbs (2006)	PSF (Hook, PS)	CD	PTCL (lumbar C modifier)	NA	Hook; 41 (13/32), PS; 12 (4/34)	0
Wang (2012)	PS	TS	Lenke 1C	LIV selection, smaller T/L ratio	NA	NA
Demura (2013)	PSF (PS, Hybrid), ASF	CD	Lenke 1C	preop. CD	42 (22/53)	NA
Chang (2014)	PS	CD	Lenke 1234C	NA	5 (8/148)	0
Ishikawa (2017)	PS	CD	Lenke 1C, 2C	LIV selection, preop. coronal imbalance to the left	14 (3/21)	0
Sullivan (2017)	PSF	CD	Lenke 1234C	preop. CD	41 (49/121)	NA

STF, selective thoracic fusion; CD, coronal decompenation; TS, trunk shift; CDI, Cotrel-Dubouset instrumentation; NA, not available; LIV, lowest instrumented vertebra; HRI, Harrington rod instrumentation; PTCL, primary thoracic and compensatory lumbar curves; L, lumbar; AVT, apical vertebral translation; T, thoracic; F.I., flexibility index; TSRH, Texas Scottish Rite Hospital; PSF, posterior spinal fusion; ASF, anterior spinal fusion; PS, pedicle screw

spinal deformities include preoperative coronal decompenation to the left; larger and stiffer lumbar curve; smaller flexibility index; smaller ratios of the thoracic curve to lumbar curve in the Cobb angle, AVT, and AVR; and persistent lumbar curve. Surgical techniques associated with postoperative coronal decompenation include thoracic curve overcorrection (to the point where the correction is greater than the preoperative flexibility on side-bending), derotation maneuver, hook pattern at LIV, and rod contour.

In the HRI era, postoperative coronal decompenation was not a significant problem in cases with LIV at the SV and NV, as proposed by King and Moe. However, postoperative coronal decompenation became a significant problem in the CDI era, even in cases following the King-Moe's rule on LIV selection^{18,19,35,37,88,89}.

Thoracic curve overcorrection using a derotation maneuver, larger lumbar curve, or LIV selection was a major causative factor in the CDI era^{19,20,33-37,61,70,74,75,88,90-92}. In contrast, a large thoracic curve correction with appropriate LIV selection is less likely to result in postoperative coronal decompenation in the PS construct than in the hook construct.

This discrepancy may result from different mechanisms whereby corrective forces are applied between the hook and PS constructs. During the derotation maneuver in the posterior approach, the derotation force applied to the thoracic curve is transmitted to the lumbar curve less with the PS than with the hook construct. This difference is because PSs at the lower foundation can be used to regulate the aggravation of the lumbar curve and may even somewhat correct the uppermost portion of the lumbar curve by the derotation of LIV in the direction opposite of the thoracic curve derotation^{25,41,93,94}. Therefore, coronal decompenation is less likely after surgery using the PS construct, even when a better thoracic curve correction is achieved.

To avoid postoperative coronal decompenation using CDI, recommendations include the use of a compression mode hook instead of a distraction mode hook at the thoracolumbar junction on the thoracic concave side and the use of a reverse-bent rod. Otherwise, the distraction force imparted to the convex side of the lumbar curve aggravates the

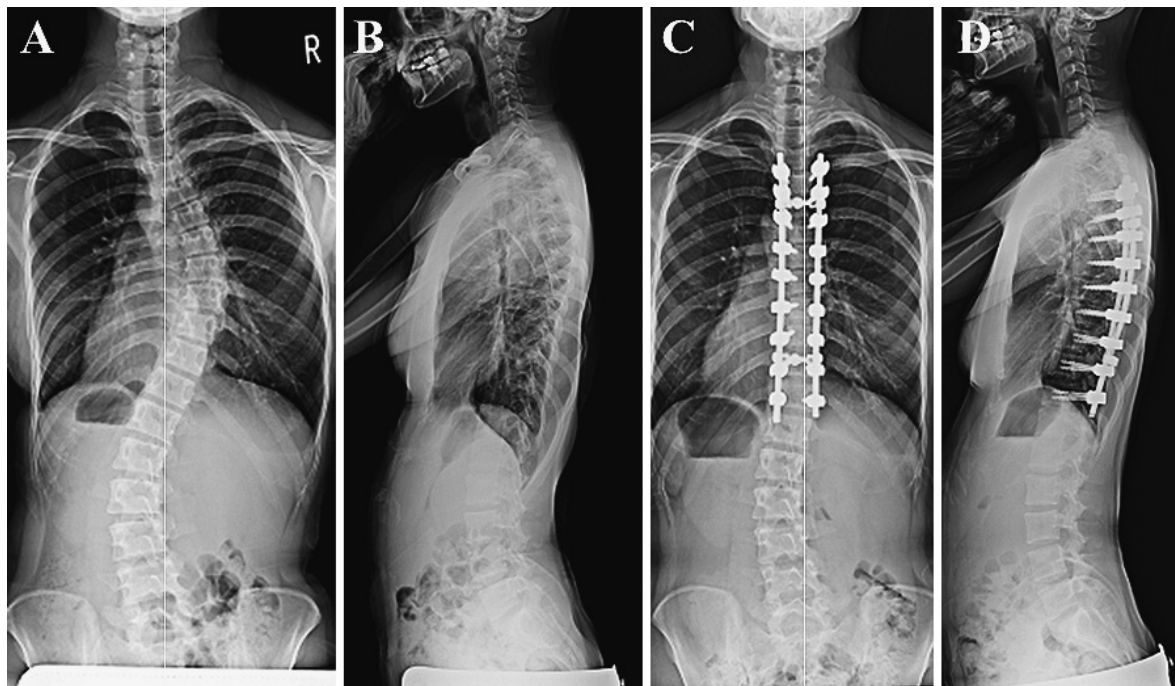


Figure 2. Representative case of an 18-year-old female adolescent idiopathic scoliosis patient with a King-Moe II/Lenke 1C curve. (A) Preoperative postero-anterior radiograph. (B) Preoperative lateral radiograph. (C) Posterior selective thoracic fusion with all-pedicle screw construct from T4 to T12 (stable vertebra). Postoperative postero-anterior radiograph taken at 6 weeks after surgery already shows acceptable spontaneous lumbar curve correction and coronal balance. (D) Postoperative lateral radiograph shows normal sagittal alignment.

lumbar curve, resulting in coronal and sagittal decompensation³⁵⁻³⁸.

Preoperative coronal decompensation to the left has been consistently reported as a major causative factor in postoperative coronal decompensation for all constructs^{39,40,46-48,54}. The reported rate of postoperative coronal decompensation after STF for patients with preoperative coronal imbalance to the left ranges from 41% to 57%, a rate higher than that for patients who were preoperatively balanced (31%)^{46,54}. The reason for this difference may be that lumbar curves with a low compensatory capacity to maintain coronal balance or persistent lumbosacral curve cannot accommodate to either the preoperative primary thoracic curve or the instrumented and corrected thoracic curve. This possibility is supported by findings that a better SLCC results in less postoperative coronal decompensation after STF^{25,41,43,54,75,76}.

Less attention has been paid to the persistent lumbosacral curve, or L4 tilt, and sacral obliquity as causative factors for postoperative coronal decompensation. Mason and Carango speculate that a greater preoperative lumbosacral angle (>15°) is a causative factor of postoperative coronal decompensation because SLCC mostly occurs between LIV and lumbar apex and less often below the lumbar apex^{19,75,76,78,80}.

Larger (>40°-45°) and stiffer lumbar curves with a low flexibility index (<25) are considered more prone to postoperative coronal decompensation^{10,19,20,34,46,62,88,90}. However, recent reports using the PS construct have demonstrated that larger and stiffer lumbar curves, including some of Lenke 3C and 4C curves, successfully responded to the instru-

mented thoracic curve without an increased rate of postoperative coronal decompensation^{26,28,95,96}.

Smaller ratios (close to 1.0) of the thoracic curve to the lumbar curve in the Cobb angle, AVT, and AVR have been identified as causative factors for postoperative coronal decompensation with CDI^{18,88}. Using a cut-off value of 1.2 for this ratio may not necessarily guarantee successful postoperative outcomes on coronal balance or lumbar curve, as shown using a recent PS construct^{26,28,29}. However, patients with a greater difference in size, particularly in the AVT between the thoracic and lumbar curves, are still considered to be more safely treated with STF^{22,42,44,75}.

While conflicting recommendations are reported for LIV selection, most surgeons prefer LIV at SV for cases in which SV is located at or distal to the lower EV of the thoracic curve because fixation distal to SV results in postoperative coronal decompensation, whereas fusing short of EV causes postoperative curve progression^{17,18,25,33,34,38,43,44,47,48,78,87}. In the CDI era, several authors reported that STF fused to SV resulted in postoperative coronal decompensation in some cases and thus, recommended shorter fusion levels^{35,37,61,75,97}. Conversely, coronal balance seems to be well maintained after surgery if LIV is placed near SV (within one level) using a recent PS construct (Fig. 2). If LIV is placed at or just above the lumbar apex, then coronal balance often shifts to the left with decompensation due to the persistent lumbosacral curve^{45,47,48,63,76,78}. In patients with preoperative severe coronal decompensation to the left, SV is located near the thoracic apex and above the lower EV of thoracic curve. In

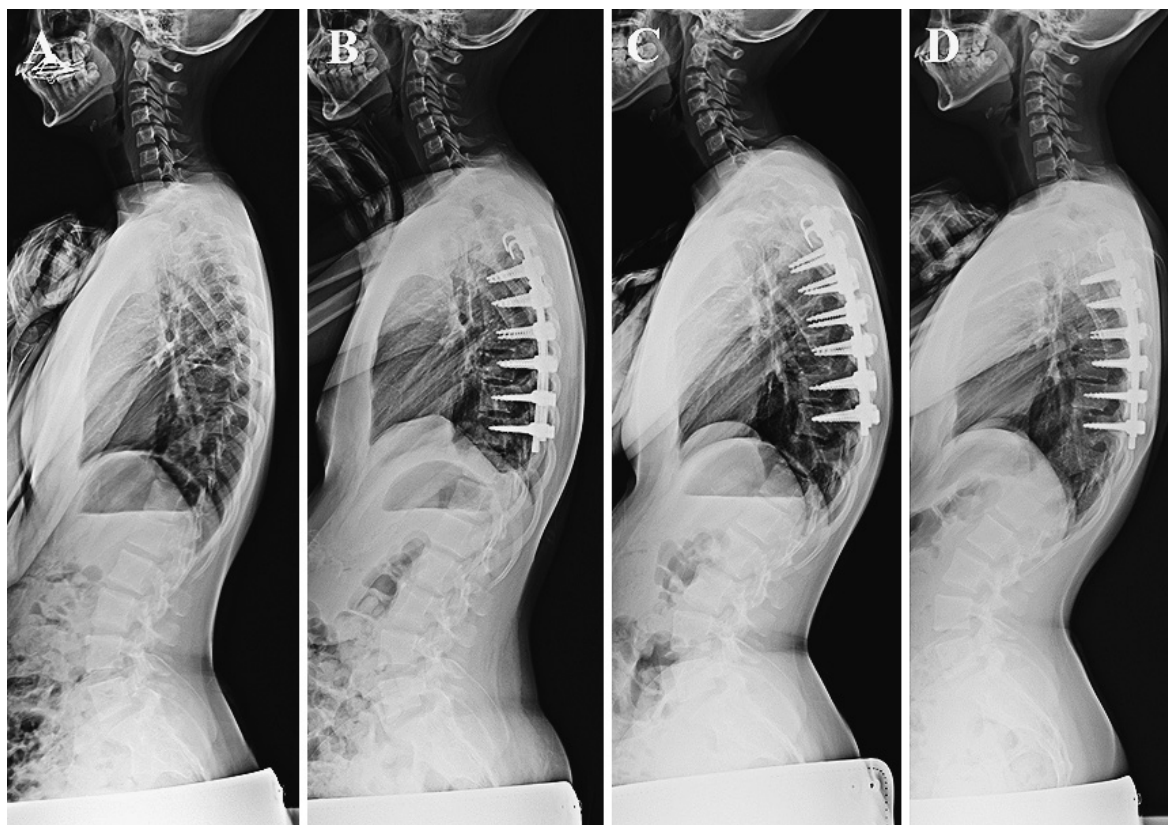


Figure 3. Representative case of a 15-year-old female adolescent idiopathic scoliosis patient with a King-Moe II/Lenke 1CN curve. (A) Preoperative lateral radiograph. (B) Posterior selective thoracic fusion from T4 to T10. Preoperative thoracolumbar kyphosis of 15° was corrected to 18° immediately after surgery. (C) Thoracolumbar kyphosis subsequently increased to 26° at 3 months after surgery. (D) The increased postoperative thoracolumbar kyphosis remains stable and has been compensated by increased lumbar lordosis thus far, as seen on the radiograph taken at 1.5 years after surgery.

such cases, LIV should be extended at least to EV to avoid postoperative curve progression, or may need to be placed beyond the lumbar apex (non-STF) because the ability of STF to maintain coronal balance after surgery may be limited^{43,45-48,54,87,98}.

Remodeling of the trunk shift or coronal imbalance, which may be attributed to postural reflex, is reported to occur in some patients after STF^{37,45,48,58,68,79,87,99} (Fig. 1). As with coronal curve correction, coronal balance usually remains stable after 2 years post surgery^{6,7,22,34,39,69}.

Thoracolumbar Kyphosis

Sagittal malalignment with a significant positive sagittal imbalance is the most significant factor influencing the patient's health status measures on back pain and function in adulthood¹⁰⁰. Therefore, achieving a normal sagittal alignment with normal thoracolumbar kyphosis after STF is mandatory and should override optimizing postoperative coronal curvature.

Reported causative factors for postoperative distal junctional kyphosis include LIV at the sagittal thoracolumbar apex, distraction mode hook placement at the thoracolumbar junction with CDI, and a significant preoperative thora-

columbar kyphosis^{22,24,31,33,36,37,39,88}. Although mild thoracolumbar kyphosis after STF is usually well tolerated during young adulthood with compensatory capacity to maintain the sagittal balance^{83,88} (Fig. 3), follow-up studies of patients aged >50 years with decreased compensatory capacity are needed to document its long-term effects on radiographic global sagittal alignment and balance and clinical outcomes.

As shown in Table 5, thoracolumbar kyphosis is maintained or slightly increases (kyphotic) after STF and decreases (lordotic) after non-STF surgery.

Conclusion

Although STF has been validated in general for the treatment of King-Moe type II or Lenke 1C curve in AIS, controversies still remain regarding surgical indications and outcomes.

Careful preoperative evaluations of the clinical appearance, radiographic parameters, and patient's expectations of the postoperative course and appropriate surgical techniques are required to achieve successful surgical outcomes for this complex spinal deformity.

Long-term impacts of residual lumbar curve, coronal decompensation, and mild thoracolumbar kyphosis on clinical

Table 5. Reported Thoracolumbar Kyphosis in Patients Treated with STF or Non-STF for Lenke 1C Curve.

Author (Year)	Curve type	Approaches or constructs	LIV for STF	Thoracolumbar kyphosis (T10-L2)					
				STF			non-STF		
				N	Preop. (°)	Final (°)	N	Preop. (°)	Final (°)
Newton (2003)	Lenke 1B, 1C	ASF, PSF	≥L1	168	-3	-	35	-2	-
Edwards (2004)	Lenke 1C, 2C	PSF (Hook+Wire/PS)	≥L1	26	-6	-1	0	-	-
		ASF		15	-3	-3	0	-	-
Chang (2007)	Lenke 1C, 2C	PS	≥L1	37	-2	-5	0	-	-
Abel (2011)	Lenke 1BC, 3BC	PSF	≥L-Apex	123	-2.3	2.7	81	-1.1	-7.5
Crawford (2013)	Lenke 1C	PSF	≥L1	138	-2.1	-	126	-0.3	-
Celestre (2015)	Lenke 1C	PSF	≥L1	38	-1.5	4.3	38	1.8	-9

STF, selective thoracic fusion; LIV, lowest instrumented vertebra; ASF, anterior spinal fusion; PSF, posterior spinal fusion; PS, pedicle screw; L, lumbar

outcomes after STF, along with optimal indications and strategy for STF, should further be assessed.

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