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REVIEW ARTICLE

Adult spinal deformity surgery: posterior three-column osteotomies vs anterior lordotic cages with posterior fusion. Complications, clinical and radiological results. A systematic review of the literature

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Abstract

Purpose The aim of our study is to analyse mid- to long-term severe adult spinal deformity (ASD) surgery outcomes by comparing three-column osteotomies (3CO) and multiple anterior interbody fusion cages (AC).

Materials and methods The PRISMA flowchart was used to systematically review the literature. Only articles with a minimum 24-month follow-up were examined, and 11 articles were included. The following radiological parameters were observed: pelvic incidence (PI), pelvic tilt (PT), lumbar lordosis (LL), sagittal vertical axis (SVA), Cobb angle and T1-sacrum plumbline. Clinical outcome was assessed using the visual analogue scale (VAS) and Oswestry disability index (ODI) scores. The main complications were analysed, and the two groups were compared.

Results Except for age, the two populations were homogeneous. Both techniques had the same number of posterior instrumented levels (7.4 ± 1.7). The AC group had a mean 3 ± 1.4 interbody fusions per patient. In the PSO group, all patients had 1 3CO and 89.8% of the osteotomies were performed at L2 or L3 vertebrae. No difference was observed between the two groups in terms of clinical outcomes. Both techniques were effective in sagittal parameters restoration with a final PI–LL mismatch = 4.4°. The PSO group had a statistically higher rate of intraoperative blood loss ($p = 0.036$), major complications, pseudoarthrosis and dural tears ($p < 0.001$).

Conclusion Both PSO and multiple AC are effective in treating ASD. Multiple AC seems more suitable when treating older patients because of a lower intraoperative blood loss, lower rate of major complications and fewer number of revision surgeries.

Keywords Adult spinal deformity · Anterior intersomatic cages · 3-column osteotomy · Pedicle subtraction osteotomy · Sagittal alignment

Introduction

Restoration of a proper sagittal and coronal alignment in adult spinal deformity (ASD) surgery represents an independent predictor of good clinical outcome. Sagittal and coronal plane under-correction have both been reported as a major cause of mechanical complications and post-operative back pain [1–4].

In sagittal plane, the surgeon must consider both global alignment and distribution of spinal curves according to pelvic incidence (PI) and Roussouly's classification [1, 5]. The choice of the surgical strategy is based on the degree of necessary correction, as well as the location and flexibility of the deformity [6]. Posterior corrective strategies including posterior column osteotomies, interbody arthrodesis and posterolateral fusion are widely described in the literature. In cases of rigid deformity with a loss of lumbar lordosis (LL) more than 25° (LL–PI mismatch > 25°), three-column osteotomies (3CO) are conventionally used. Nevertheless, 3CO present a high incidence of peri- and post-operative complications [6–9].

Recently, multiple lordotic or hyperlordotic interbody cages via anterior lumbar approaches have been proposed as an alternative corrective strategy to vertebral osteotomies [9–14].

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To the best of our knowledge, there are no review articles available in the literature that specifically focus on the role of multiple lordotic or hyperlordotic interbody cages via anterior lumbar approaches versus 3CO in severe ASD. Furthermore, the available literature does not clarify which surgical strategy should be preferred based on the different deformity patterns.

The aim of this paper is to compare and critically analyse mid- to long-term complications, clinical and radiological results of these two different corrective strategies to determine the profile of the most well-suited patients for these two different surgical approaches.

Materials and methods

A systematic review of the available literature was performed to identify all studies dealing with surgical ASD treatment. The research was performed based on the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Fig. 1). Medline was

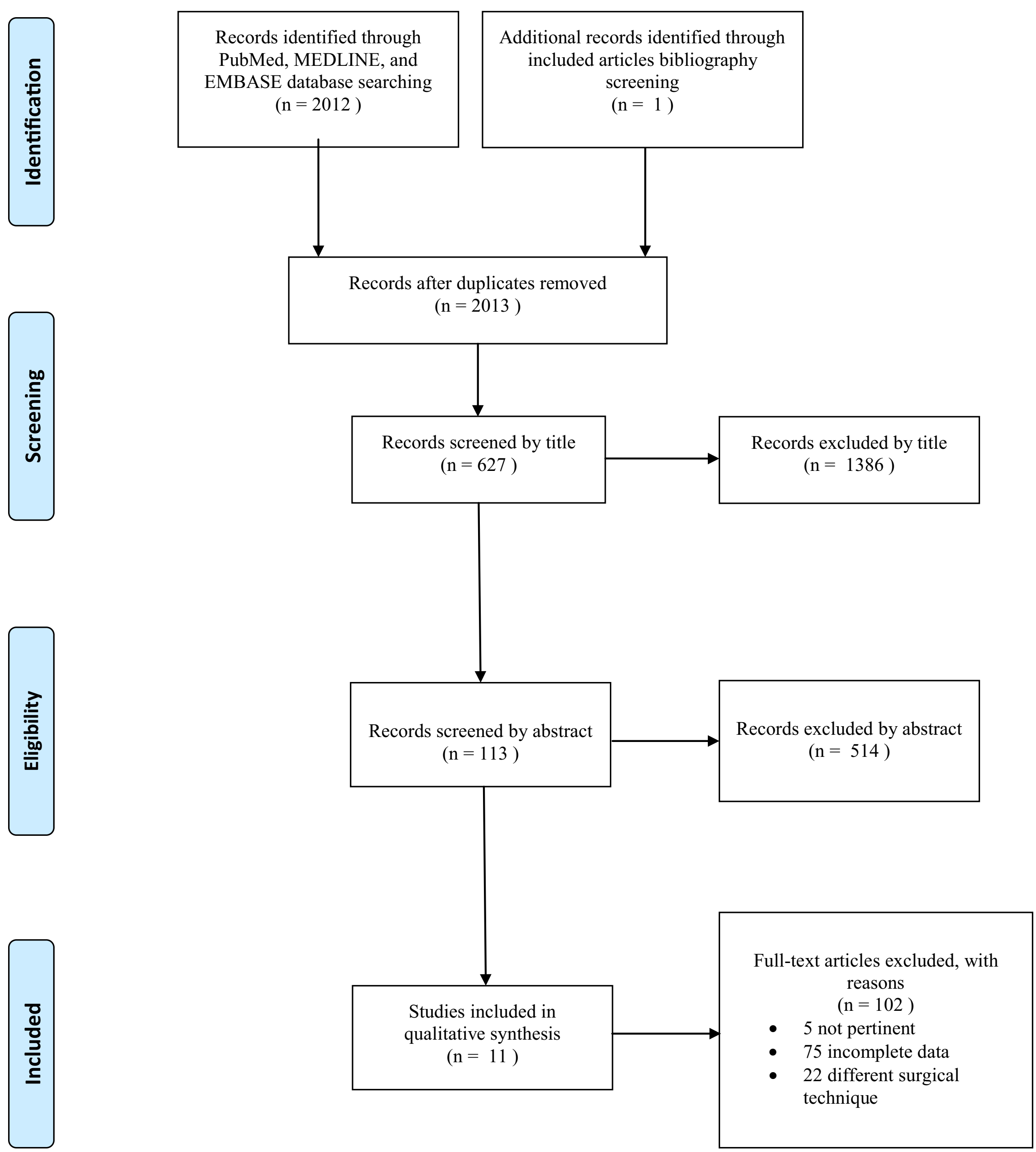

Fig. 1 PRISMA flowchart for the search and inclusion strategy

searched through PubMed, Google Scholar, Embase and the Cochrane Central Register of Controlled Trials.

The research was performed using the following keywords and MeSH terms: “adult scoliosis”, “adult spinal deformity”, “correction”, “osteotomies”, “ALIF”, “LLIF”, “XLIF”, “OLIF”, “ACR” and “lumbar interbody fusion”.

We included retrospective or prospective studies in English, which counted randomized controlled trials, non-randomized trials, cohort studies and case–control studies with at least 24 months of mean follow-up; to level out the final result, we only included articles reporting exhaustive data on sagittal and coronal plane corrections, clinical outcomes and complications. Only articles reporting results on high-grade deformities (PI–LL mismatch > 25° or severe lumbar hypolordosis (< − 20°)) requiring multiple levels fusion were included.

All non-English articles, animal studies, cadaveric studies, case reports, literature reviews, meta-analyses, technical notes, expert opinions and editorial letters were excluded. In case of articles reporting comparative results between different anterior and posterior interbody fusion techniques, only the anterior surgeries data were considered for our analysis.

The following data were extracted: number of patients, population mean age (years), gender distribution, mean follow-up (months), indications for surgery, data on surgical technique (surgical time, intraoperative blood loss, ALIF, LLIF, OLIF, XLIF, ACR, PSO, number of fused levels, number of interbody fusions, number of PSO per patient), radiological parameters (PI, PT, LL, Cobb’s angle, SVA, T1 plumbline—sacrum distance), clinical results (ODI and VAS scores) and complication rates.

The studies were assigned a level of evidence based on the 2011 Oxford Centre for Evidence-based Medicine Levels of Evidence [15].

Statistical analysis

Statistical analysis was performed using the SPSS version 20.0 for Windows (IBM Corporation, Armonk, NY, USA). Categorical variables were expressed as number of cases and percentage. Continuous variables were reported as mean ± standard deviation (SD); means were compared with the paired t test. Comparison among different groups for continuous variables was assessed using the nonparametric Mann–Whitney test, while for ordinal variables, the Fisher exact test was used. Two-sided p values and/or 95% confidence interval (CI) were reported, and significance was accepted at $p < 0.05$.

Results

Eleven articles were eventually included in the study [16–26]. Two articles were LoE 3 [21, 25] and 9 were LoE 4 [16–20, 22–24, 26]. Six articles reported results using PSO (PSO group) [16–18, 20, 22, 26], while 4 articles reported about anterior minimally invasive fusion techniques (ALIF, LLIF, OLIF) (AC group) [19, 23–25]; 1 article compared PSO versus OLIF [21].

The articles included 314 patients: 166 underwent a correction with PSO, whereas 148 had a deformity correction using an anterior interbody fusion approach first, followed by a second posterior instrumentation. The mean age at surgery was 62.5 ± 9.7 years (CI 95% 55.9 to 70) (PSO: 57.1 ± 10.4 Vs AC: 68.9 ± 2.4; $p = 0.0362$); the mean FU was 38.9 ± 14.9 months (CI 95% 29.5 to 48.4) (PSO: 42.9 ± 18.1 Vs AC: 33.4 ± 7.4; $p = 0.2993$); and 86% of the patients were females. Table 1.

The principal indications for surgery were ASD, degenerative scoliosis, flat back syndrome and post-traumatic spinal deformities.

Table 1 Demographic data: LoE, level of evidence; FU, follow-up; ALIF, anterior lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; OLIF, oblique lumbar interbody fusion; PSO, pedicle subtraction osteotomy

AUTHOR	LoE	N° Patients	M:F	Technique	Mean Age (years)	Mean FU (months)
Noun et Al. (2000) [22]	4	10	1:9	PSO	–	24
Berven et Al. (2001) [16]	4	13	5:8	PSO	45.1	57
Bridwell et Al. (2003) [18]	4	27	4:23	PSO	52.4	24
Boachie-adjei et Al. (2006) [17]	4	24	7:17	PSO	48	48
Hyun et Al. (2010) [20]	4	13	2:11	PSO	59	73
Toyone et Al. (2012) [26]	4	14	–	PSO	67	32
Lee et Al. (2019) [21]	3	65	2:63	PSO	71	42.2
		41	2:39	OLIF	72	25.1
Crandall et Al. (2009) [19]	4	20	3:17	ALIF	68	45
Park HY et Al. (2018) [23]	4	48	7:41	LLIF	69.2	33.6
Park SW et Al. (2020) [24]	4	13	2:11	OLIF	69.8	29.8
Saigal et Al. (2020) [25]	3	26	7:19	ACR	65.5	33.6

Apart from the population age, which was statistically lower in the PSO group, the two populations were homogeneous considering surgical, clinical and radiological parameters.

Surgical data

The mean instrumented vertebrae number was 7.4 ± 1.7 (CI 95% 5.8 to 9) (PSO group: 7.4 ± 2.3 (CI 95% − 12.9 to 27.7), AC group: 7.4 ± 1.8 (CI 95% 5.2 to 9.6); $p = 0.9904$) [19–21, 23–25]. All patients treated with the 3CO technique had only 1 PSO performed at the following levels: 3 at T12 (1.8%), 3 at L1 (1.8%), 78 at L2 (47%), 71 at L3 (42.8%), 8 at L4 (4.8%) and 3 at L5 (1.8%).

With reference to the AC group, 3 ± 1.4 levels (CI 95% 1.3 to 4.8) of interbody fusion per patient were performed. One article in the AC group reported data on anterior hyperlordotic cages (20° or 30°): in this case, the mean number of interbody fusions was 1.2 levels per patient [25].

The mean operative time was 384 ± 141.3 min (CI 95% 275.4 to 492.1); this parameter was slightly lower in the PSO group, but the difference was not statistically significant (PSO: 381.9 ± 176.3 min Vs AC: 388.3 ± 45.8 min; $p = 0.297$). Overall blood loss was 1870.7 ± 894 ml (CI 95% 1231.2 to 2510.3); the PSO group had a statistically significant higher blood loss compared to the AC group (2299 ± 724.7 ml Vs 1228.3 ± 778.1 ml; $p = 0.036$) Table 2.

Clinical outcome

The VAS back score was reported in 7 of the articles included in our scope of analysis [18, 19, 21–24, 26]: the difference from pre-operation to last FU was 3.8 ± 1.4 points (CI 95% 2.6 to 5) ($p < 0.05$). The two different groups did not show any statistically significant differences, with Δ 4.3 ± 1.3 points in the PSO group and Δ 3.4 ± 1.1 points in the AC group ($p = 0.386$).

Table 2 Surgical specifics: ALIF, anterior lumbar interbody fusion; LLIF, lateral lumbar interbody fusion; OLIF, oblique lumbar interbody fusion; PSO, pedicle subtraction osteotomy; ADS, adult degenerative scoliosis; ASD, adult spinal deformity

AUTHOR	Technique	Instrumented vertebrae	Interbody fused/PSO levels	Surgical time (minutes)	Blood loss (ml)	Diagnoses
Noun et Al. (2000) [22]	PSO (L3, 7; L4, 2; L2, 1)	–	1	210 (180–360)	1800 (1500–2500)	11 ADS, 9 flat back
Berven et Al. (2001) [16]	PSO (L3, 8; L4, 3; L5, 2)	–	1	–	–	8 flat back; 3 ankylosing-spondylitis; 2ADS
Bridwell et Al. (2003) [18]	PSO (L1, 1; L2, 8; L3, 18)	–	1	720 (408–1128)	2396 (500–6650)	14 idiopathic scoliosis; 8 ADS; 3 traumatic kyphosis; 2 ankylosing-spondylitis
Boachie-adjei et Al. (2006) [17]	PSO (L3, 15; L2, 6; L4, 2; L5, 1)	–	1	304 (180–480)	2700 (420–6700)	16 flat back, 3 traumatic scoliosis; 2 ankylosing-spondylitis; 1 ADS; 1 lumbar spondylosis; 1 kyphoscoliosis
Hyun et Al. (2010) [20]	PSO (T12, 3; L1, 2; L3, 7; L4, 1)	5.8	1	385 (275–550)	2984 (1000–5500)	Sagittal imbalance
Toyone et Al. (2012) [26]	PSO (L3,14)	–	1	310 (245–375)	1090 (700–2900)	14 ASD
Lee et Al. (2019) [21]	PSO (L2, 63; L3, 2)	9	1	362,4 ± 35,4	2824 ± 509,8	106 ASD
	OLIF	9	3	379 ± 46	1736,6 ± 465,7	
Crandall et Al. (2009) [19]	ALIF	7.6	4.4	–	–	–
Park HY et Al. (2018) [23]	LLIF	4.7	2.2	438	1966	48 ASD
Park SW et Al. (2020) [24]	LLIF	6.8	4.4	347,9	260,7	13 ASD
Saigal et Al. (2020) [25]	ACR (L1L2, 9; L2L3, 8; L3L4, 5; L4L5, 9)	9	1.2	–	950	Iatrogenic flat back disease

The ODI score globally passed from a pre-operative 46.3 ± 11.3% (CI 95% 35.7 to 57) to a final FU 26.1 ± 12.2% (CI 95% 14.9 to 39) value (Δ 20.3 ± 8.1%; $p < 0.05$) [18–21, 23, 24]. When comparing the PSO group Vs the AC group, no statistically significant difference (Δ18.9 ± 5.5% Vs Δ 21.3 ± 10.4%; $p = 0.738$) emerged. In all cases, the pre- to post-operative ODI difference was higher than the reported minimum clinically significant difference of ODI (11%) [27].

Finally, the VAS leg score showed a significant improvement after surgery, with a final FU Δ 4 ± 1.8 points (CI 95% 1.2 to 6.8) ($p < 0.05$). Also in this case, no statistically significant difference was observed between the two groups ($p = 0.554$) Table 3.

Radiological parameters

Sagittal plane With reference to the sagittal plane, 3 parameters were mainly reported: PT, LL and SVA; all these parameters showed an important post-operative improvement that was maintained at last FU.

PI mean value was 53.3 ± 2° (CI 95% 51.2 to 55.4) [19, 21, 23, 24, 26]; no statistically significant difference was observed in the two groups ($p = 0.8355$).

As regards PT values, the two groups had no difference in pre-operative PT ($p = 0.1302$) (PSO PT: 35.4 ± 5.2°; AC PT: 29.5 ± 2.8°). From pre-op to last FU, the mean global variation was − 10.5 ± 6.1° (CI 95% 4 to 16.9) ($p < 0.05$) [21, 23–26]. No statistically significant difference was noted between PSO group corrective potential compared to the AC group (Δ − 12.2 ± 7.4° (CI 95% − 53.9 to 78.3) Vs Δ − 9.6 ± 6.5° (CI 95% − 0.7 to 19.9); $p = 0.643$).

Lumbar lordosis was reported in all articles. No statistically significant difference was observed in pre-operative LL between the two groups ($p = 0.1773$). All techniques demonstrated a great LL corrective power, with global PI-LL mismatch decreasing from 41.7° before surgery to 4.4° after surgery ($p < 0.05$). The global variation in LL was Δ 36.9 ± 22.3° (CI 95% 22.7 to 51), with the lordosis value improving from − 11.9 ± 10.7° (CI 95% − 18.8 to − 5.2) before surgery to − 48.8 ± 13.2° (CI 95% − 57.2 to − 40.4) at last FU ($p < 0.05$); the PSO technique demonstrated that it has a major corrective power compared to the AC. The difference, however, was not statistically significant ($p = 0.219$): the PSO group had a mean LL variation of Δ 41.5 ± 16.8°, while the AC group showed a Δ 30.3 ± 29.1° improvement in LL at last FU.

With reference to the AC group, the mean LL variation was associated with the number of interbody levels fused and a separate analysis was carried out in case of multiple level non-hyperlordotic AC and hyperlordotic AC. In case of multiple level non-hyperlordotic AC, each patient had a mean 3.5 ± 1.1 (CI 95% 1.8 to 5.2) interbody fusion levels with a mean LL Δ 30.3 ± 33.6° (CI 95% − 23.157 to 83.757):

Table 3 Clinical outcomes.

AUTHOR		VAS Back Pre	VAS Back last FU	Δ VAS Back	VAS Leg Pre	VAS Leg last FU	Δ VAS Leg	ODI Pre	ODI last FU	Δ ODI
Noun et Al. (2000) [22]		8	4	4	–	–	–	–	–	–
Berven et Al. (2001) [16]		–	–	–	–	–	–	–	–	–
Bridwell et Al. (2003) [18]		7	4.4	2.6	–	–	–	51.2	35.8	15.8
Boachie-adjei et Al. (2006) [17]		–	–	–	–	–	–	–	–	–
Hyun et Al. (2010) [20]		–	–	–	–	–	–	55.4	30.2	25.2
Toyone et Al. (2012) [26]		6.1	0.9	5.2	–	–	–	–	–	–
Lee et Al. (2019) [21]	PSO	7.7	2.4	5.3	6.5	2.4	4.1	29.5	13.8	15.7
	OLIF	7.3	2.6	4.7	6.1	2.2	3.9	30.1	14.8	15.3
Crandall et Al. (2009) [19]		6.5	3.3	3.2	–	–	–	52	28.2	23.8
Park HY et Al. (2018) [23]		6.5	5.3	1.2	6.7	4.8	1.9	56.5	45.3	11.2
Park SW et Al. (2020) [24]		6.4	2.1	4.3	7.6	1.4	6.2	49.7	14.9	34.8
Saigal et Al. (2020) [25]		–	–	–	–	–	–	–	–	–

VAS, visual analogue scale; FU, follow-up; Δ, difference; pre, pre-operative; post, postoperative; ODI, Oswestry Disability Index; LLIF, lateral lumbar interbody fusion; OLIF, oblique lumbar interbody fusion; PSO, pedicle subtraction osteotomy this corresponds to 8.7° LL correction per level. On the other hand, the AC hyperlordotic article reported 30.2° mean post-operative LL improvement with 1.2 interbody fusion levels per patient, which corresponds to 25.2° correction per level fused.

The final sagittal parameter analysed was the SVA [16–18, 20–24, 26]. Also this parameter showed an important post-operative global improvement that was maintained at last FU, Δ 107.9 ± 60.1 mm (CI 95% 64.9 to 150.9) (p < 0.05). In this case too, 3CO proved to have a major corrective power, but once again the difference with AC was not statistically significant: PSO Δ 109.5 ± 48.9 mm (CI 95% 64.3 to 154.7) Vs AC group Δ 104.1 ± 95.3 mm (CI 95% − 132.6 to 340.9) (p = 0.394).

Table 4 displays the main sagittal radiological parameters analysed.

Displayed in Table 5 are the results of the nonparametric Mann–Whitney test.

Coronal plane Two radiological parameters were considered with a view to analysing the coronal plane corrective potential of ASD surgery: the Cobb angle, which presented a mean global variation Δ 21 ± 7.1° (CI 95% 3.4 to 38.6) (pre 29.9 ± 10,4° Cobb (CI 95% 4.2 to 55.7); post 8.9 ± 3.3° Cobb (CI 95% 0.8 to 17); p = 0.1326) [19, 23, 26], and the coronal imbalance, assessed with the T1 to mid sacrum line, which was globally corrected at last FU of Δ 11.6 ± 7.3 mm (CI 95% 2.6 to 20.6) with a final value of 13.6 ± 4.3 mm (CI 95% 8.2 to 18.9) (p < 0.05) [16, 17, 22, 23, 26] (Table 6).

With reference to coronal parameters, no comparison could be made between the PSO and the AC groups because of the paucity of available data.

Complications

The long-term effectiveness of ASD surgery was also evaluated taking account of the rate of major complications that were considered as follows: pseudoarthrosis, proximal junction kyphosis (PJK), dural tears and postoperative permanent, or leading to a re-intervention, neurological complaint. The overall number of reported major complications was 97 events in 314 patients, i.e. 30.9% incidence (37 pseudoarthrosis cases (11.8%), 40 PJK's (13.7%), 11 intraoperative dural tears (3.5%) and 6 severe post-operative neurological complaints (1.9%)). The global re-intervention rate was 9.5% (30/314 patients) (Table 7).

The PSO group reported 41.6% major complications (69/166) that lead to a 12% re-intervention rate (20/166) (32 pseudoarthrosis (20.9%), 21 PJK's (12.7%), 11 dural tears (6.6%) and 5 postoperative severe neurological complaints (3%)). On the other hand, the AC group reported 18.9% major complications (28/148 patients) that lead to 10

Table 4 Sagittal radiological parameters: PI, pelvic incidence; PT, pelvic tilt; LL, lumbar lordosis; SVA, sagittal vertical axis; Δ, difference; °, degree; mm, millimetres; pre, pre-operative; post, postoperative; LLIF, lateral lumbar interbody fusion; OLIF, oblique lumbar interbody fusion; PSO, pedicle subtraction osteotomy

AUTHOR		PI (°)	PT Pre (°)	PT Last FU (°)	Δ PT (°)	LL Pre (°)	LL Last FU (°)	Δ LL (°)	SVA pre (mm)	SVA last FU (mm)	Δ SVA (mm)
Noun et Al. (2000) [22]		-	-	-	-	− 11	− 42	31	72	15	57
Berven et Al. (2001) [16]		-	-	-	-	− 15.5	− 45.4	29.9	145	54	91
Bridwell et Al. (2003) [18]		-	-	-	-	− 14.5	− 48.6	34.1	177	42	135
Boachie-adjei et Al. (2006) [17]		-	-	-	-	− 13	− 54	41	124	20	104
Hyun et Al. (2010) [20]		-	-	-	-	− 14	− 46.3	32.3	115	32	83
Toyone et Al. (2012) [26]		52	39	32	7	3	− 42	45	120	30	90
Lee et Al. (2019) [21]	PSO	55.1	31.7	14.3	17.4	6.5	− 71	77.5	212.9	6.1	206.8
	OLIF	54.2	27.6	11.9	15.7	1	− 73.2	74.2	202.7	0.7	202
Crandall et Al. (2009) [19]		55.1	-	-	-	− 30.7	− 32.2	1.5	-	-	-
Park HY et Al. (2018) [23]		50	26.7	25.4	1.4	− 22.7	− 29.4	6.7	76.5	64.8	11.6
Park SW et Al. (2020) [24]		53.2	31.4	17.6	13.8	− 16.7	− 55.5	38.8	125.9	27.1	98.8
Saigal et Al. (2020) [25]		-	32.4	24.8	7.6	− 16.1	− 46.3	30.2	-	-	-

Table 5 Mann–Whitney test results

	PSO group		AC group		Mann–Whitney
Parameter	n° patients	Mean ± SD	n° patients	Mean ± SD	*p value*
Surgical time	153	384 ± 141.3	102	388.3 ± 45.8	0.297
Blood loss	153	2299 ± 724.7	120	1228.3 ± 778.1	0.036
VAS back	116	4.3 ± 1.3	122	3.4 ± 1.6	0.386
VAS leg	65	4.1 ± 0.1	102	4.0 ± 2.2	0.554
Δ ODI	105	18.9 ± 5.5	122	21.3 ± 10.4	0.738
Δ PT	79	12.2 ± 7.4	128	9.6 ± 6.5	0.643
Δ LL	166	41.5 ± 16.8	148	30.3 ± 29.1	0.219
Δ SVA	166	109.5 ± 48.9	102	85.7 ± 86.2	0.394

PSO pedicle subtraction osteotomy; *AC* anterior cages; *SD* standard deviation; *VAS* visual analogue scale; *ODI* Oswestry Disability Index; *PT* pelvic tilt; *LL* lumbar lordosis; *SVA* sagittal vertical axis; Δ, difference

Table 6 Coronal radiological parameters

AUTHOR		Cobb Pre (°)	Cobb Last FU (°)	Δ Cobb (°)	Coronal imbalance pre (mm)	Coronal imbalance last FU (mm)	Δ Coronal imbalance (mm)
Noun et Al. (2000) [22]		–	–	–	30	20	10
Berven et Al. (2001) [16]		–	–	–	29	11	18
Bridwell et Al. (2003) [18]		–	–	–	–	–	–
Boachie-adjei et Al. (2006) [17]		–	–	–	23	16	7
Hyun et Al. (2010) [20]		–	–	–	–	–	–
Toyone et Al. (2012) [26]		40	12	28	30	10	20
Lee et Al. (2019) [21]	PSO	–	–	–	–	–	–
	OLIF	–	–	–	–	–	–
Crandall et Al. (2009) [19]		30.5	9.3	21.2	–	–	–
Park HY et Al. (2018) [23]		19.3	5.5	13.8	13.8	10.9	2.9
Park SW et Al. (2020) [24]		–	–	–	–	–	–
Saigal et Al. (2020) [25]		–	–	–	–	–	–

Pre pre-operative; *Post* post-operative; Δ, difference; °, degree; *mm* millimetres; *LLIF* lateral lumbar interbody fusion; *OLIF* oblique lumbar interbody fusion; *PSO* pedicle subtraction osteotomy

re-interventions (6.8%) (5 pseudoarthrosis (3.4%), 22 PJK's (14.9%) and 1 persistent neurological deficit (0.7%)).

The complications incidence in the two groups was analysed with the Fisher exact test and a statistically significant difference was observed in terms of the global rate of major complications, the rate of pseudoarthrosis and the rate of dural tears that were more frequent in the PSO group ($p < 0.001$) (Table 8).

Discussion

Adult spinal deformity is nowadays a wide clinical problem and affects up to 60% of the adult population [28, 29]. As the elderly population is becoming increasingly demanding, several surgical options have been developed. In the past, the most frequently used approach was posterior open surgery with vertebral osteotomies with the PSO being used to correct severe ASD. Unfortunately, these surgical strategies have high morbidity and postoperative complications rates [7–9, 30, 31].

In recent years, multiple lordotic or hyperlordotic interbody cages via anterior lumbar approaches (ALIF, LLIF, OLIF and ACR) have been used in combination with posterior instrumentation and fusion as a modular corrective strategy to treat severe ASD; this has allowed to minimize complication rate [10, 11, 13]. The literature has shown that general and surgical complications increase on the basis of patients' age and type of surgery, due to the presence of comorbidities [7].

Analysing the data extracted in this review, the population of the AC group is older than the PSO group ($p = 0.0362$).

Table 7 Complications: PJK, proximal junctional kyphosis; LLIF, lateral lumbar interbody fusion; OLIF, oblique lumbar interbody fusion; PSO, pedicle subtraction osteotomy; ASD, adjacent segment disease; sd, syndrome

AUTHOR		Pseudoarthrosis	PJK	Dural tears	Neurological injury	Re-intervention	Other
Noun et Al. 2000 [22]		–	–	–	1 (chronic intercostal neuralgia)	1 (for coronal imbalance)	–
Berven et Al. 2001 [16]		–	1	3	4 (*transient* paresis)	1 (for PJK)	1 pulmonary embolus
Bridwell et Al., 2003 [18]		7	–	2	1 (urinary retention, bony postop canal stenosis)	5 (4 pseudoarthrosis; 1 canal stenosis)	1 myocardial infarction; 1 laparotomy for abdominal compartment sd; 2 deep vein thrombosis; 1 unilateral visual field defect
Boachie-adjei et Al., 2006 [17]		3	–	4	3 (intraop nerve root injury; epidural hematoma; postop canal stenosis)	7 (1 coronal imbalance; 1 epidural hematoma; 1 wound inf; 3 pseudoarthrosis; 1 spinal stenosis)	1 wound infection
Hyun et Al., 2010 [20]		–	3	1	1 (spinal cord compression)	4	2 massive bleeding; 5 rod breakage
Toyone et Al., 2012 [26]		–	–	1	–	2 (hook dislodgements)	1 rod breakage (no reoperation)
Lee et Al., 2019 [21]	PSO	22	17	–	–	–	–
	OLIF	1	9	–	–	–	–
Crandall et Al., 2009 [19]		4	–	–	1 (footdrop) (*transient*)	4 (2 pseudoarthrosis, 2 ASD)	5 ASD; 2 wound infections
Park HY et Al., 2018 [23]		–	9	–	18 (4 motor weakness, 14 numbness) (*transient*)	3 (1 hematoma evacuation, 2 PJK)	1 incisional hernia
Park SW et Al., 2020 [24]		–	4	–	13 (8 psoas weakness; 5 leg numbness) (*transient*)	3	
Saigal et Al., 2020 [25]		–	–	–	1 (motor weakness) (*permanent*)	–	–

Table 8 Fisher exact test to assess statistically significant differences in complication rates between the PSO and the AC technique groups: PSO, pedicle subtraction osteotomy; AC, anterior cages; PJK, proximal junctional kyphosis

Parameter	PSO group (all cases = 166) n of events (%)	AC group (all cases = 148) n of events (%)	*p* value (Fisher exact test)
All complications	64 (41.6)	28 (18.9)	< 0.001
Pseudoarthrosis	32 (20.9)	5 (3.4)	< 0.001
PJK	21 (12.7)	22 (14.9)	0.498
Dural tears	11 (6.6)	0 (0)	< 0.001
Neurological complaints	5 (3)	1 (0.7)	0.226
Re-intervention	20 (12)	10 (6.8)	0.307

A plausible hypothesis is that for older patients with more comorbidities, the authors of the studies we included have chosen a multiple lordotic or hyperlordotic interbody cages approach to minimize surgical effort and complications rate.

Actually, a statistically significant higher blood loss is noted in PSO group compared to the AC group ($p = 0.036$) with a comparable number of posterior fused levels and a similar surgical time (PSO group 381.9 ± 176.3 Vs AC group 388.3 ± 45.8 min; $p = 0.297$).

Analysing complications, the PSO group presented a 41.6% major complications rate, while the AC group only had 18.9% major complications; this, respectively, corresponded to a 12% Vs 6.8% re-interventions rate ($p = 0.307$). A statistically significant difference between PSO and AC group was observed in terms of the global rate of major complications, pseudoarthrosis and dural tears ($p < 0.001$). The lower dural tear rate in the AC group is due to the fact that interbody ASD correction permits to indirectly decompress the neural structures without violating the vertebral canal and this might be an advantage, especially in revision cases where there might be a posterior scar tissue [12, 13, 32, 33]. Obviously, the indirect decompression is not always enough, especially in cases of severe central canal stenosis, and in this cases PSO might be a good surgical option to achieve both a direct neural structure decompression and a deformity correction [13].

The AC group presented a significant lower rate of long-term pseudoarthrosis with a consequent lower revision surgery rate. Several reasons can be associated with this datum: (a) anterior interbody cages allow for the achievement of a solid intersomatic fusion due to large footprint, with a lower risk of subsidence [34]; (b) the deformity correction is obtained through the structural restoration of the anterior column height which, in contrast to posterior osteotomies where the correction is based on shortening of the posterior column and lengthening of anterior degenerated disc spaces, may prevent the loss of correction at long-term FU [35]; (c) anterior supports reduce rotational instability compared to PSO [36]; (d) multiple cages permit a modular restoration of lumbar lordosis avoiding an angular correction of the deformity and, hence, an increase in the mechanical stress on the hardware (rods, screws) and on instrumented vertebrae; in case of hyperlordotic cages, an angular correction is performed but the large footprint of the anterior support decreases the mechanical stress on the hardware [12]; (e) interbody fusion at the lumbosacral junction plays a major role in preventing non-union and hardware failure [36].

In the AC group, the most common complications observed were transient neurological complaints mainly associated with LLIF and OLIF approaches [23, 24]: both these techniques are known to cause postoperative transient neurological signs due to manipulation of the psoas muscle and lumbar plexus; normally such symptoms, as in the case of our review, disappear within 3 to 6 months [21, 32].

From a clinical point of view, both types of surgery resulted to be satisfactory at a minimum 2-year FU. The pre- to post-operative ODI differences were higher than the reported minimum clinically important differences of ODI (11%) for both procedures [27]. Interestingly, the comparative analysis between two corrective strategies, despite significant higher complications rate in PSO population, does not highlight significant differences in medium- to long-term clinical results. The explanation of this point might be given by Ayhan et al. who demonstrated that high rate of perioperative complications has no or minimal effects on the final clinical outcome because the greatest improvements in quality of life are gradual and are experienced during in the first year after surgery [37].

Actually, the correlation between proper restoration of sagittal alignment, clinical outcomes and postoperative mechanical complications has been widely established in literature [38, 39]. The results of our review confirm the efficacy of ASD surgery in achieving coronal and sagittal alignment with both the PSO and the AC techniques, with no statistically significant difference emerging in spino-pelvic parameters correction.

As previously demonstrated, a final PI–LL mismatch < 10° should be obtained [40], but more specifically the lordosis should be tailored to each patient spinal type according to Roussouly [5]. A commonly accepted rule is that 2/3 of the lumbar lordotic curve should be between L4 and S1, but in our review only 6.6% of PSO (8 at L4 and 3 at L5 out of a total of 166 3CO) were performed at lower lumbar levels. In fact, even if some authors have demonstrated its feasibility [41], due to technical difficulties PSO is generally performed at L4 or above and rarely at L5. ALIF or OLIF cages can instead be easily implanted at L5S1 level, which seems to be more suitable in restoring lower lumbar lordosis in a physiological manner for Roussouly types 1 and 2 [12, 13, 42]. Moreover, correcting the lordosis at L5S1 might result in a reduction of PT: the literature suggests that the more the correction is applied caudally, the better PT improvement is achieved, with good potential correction of the SVA [12, 43].

In this scenario, the PSO might not be the best option as it results in an angular correction that normally is performed at the L2 or L3 vertebrae, as is confirmed by our review (89.9%); an alternative option might be the anterior hyperlordotic cages that permit to obtain a correction very close to the 30° achievable with a PSO [12, 43–45]. Our review confirms this hypothesis; in fact, the only article reporting on anterior hyperlordotic cages had a LL variation of 25.2° per implanted cage which is much more than the 8.7° correction per cage obtained by the non-hyperlordotic cages of this review.

An approach using multiple level AC may allow to achieve a more harmonious and physiological LL correction. Considering the most physiological LL correction as possible based on each patient case, hyperlordotic ALIF or OLIF cages at lower lumbar levels appear a valid solution in Roussouly type 1 and 2 cases; on the other hand, in Roussouly type 3 and 4 cases, based on the patients' age, global performance status and deformity pattern, the surgeon might opt for an apical PSO or a multimodal AC correction using different techniques.

Furthermore, the results of our review demonstrate that both surgical strategies are effective on the coronal plane correction; however, the two groups could unfortunately not be compared under this aspect because the PSO group articles reported mainly the T1 to sacrum coronal balance parameter while the AC cages group reported mainly the Cobb angle variations. Nevertheless, it is reasonable to state that, in case of rigid and severe coronal deformities, mainly of congenital aetiology, or in case of previous AC correction surgery with a persistent coronal or sagittal imbalance, 3CO and asymmetric PSO, in need be, can be the best solution [46].

To the best of our knowledge, there are no review articles available in the literature specifically focusing on mid- to long-term results of multiple interbody cages via anterior lumbar approaches versus three-column osteotomies in severe ASD corrective surgery. Nevertheless, we are fully aware of the inherent limitations of this study. The articles included have low levels of evidence (III or IV). Surgical indications of the included population were highly variable. The long-term data regarding complications, clinical and radiological results of multiple lordotic and mainly of hyperlordotic interbody cages, are limited.

Conclusion

In conclusion, we may state that both 3CO and multiple level AC have a good clinical and radiological outcome in treating severe ASD at mid- to long-term FU. PSO demonstrate no statistically significant difference in spino-pelvic parameters correction. The AC group reported a lower rate of major intraoperative complications, intraoperative blood loss, dural tears and long-term pseudoarthrosis, with fewer revision surgeries required: these elements must all be taken into account if considering a surgical treatment in elderly patients. Furthermore, multiple level AC, using hyperlordotic cages and different surgical strategies (ALIF, LLIF, OLIF, ACR), if need be, makes it possible to correct the LL and, consequently, realign the spine considering each patient Roussouly type. Both approaches proved to be clinically effective in ASD corrective surgery.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This is a systematic review of the literature, and no ethical approval was necessary for this study.

Informed consent Informed consent was not applicable to this study.

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