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Closing-Opening Wedge Osteotomy for the Treatment of Sagittal Imbalance

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Study Design. Closing-opening wedge osteotomy (COWO) had been performed by the senior author (K.C.) since 1998. A study had been conducted to evaluate the efficacy of COWO since 2000.

Objective. Assess COWO for sagittal imbalance requiring more than 35° lordotic correction at the level of osteotomy.

Summary of Background Data. Correction of sagittal imbalance commonly uses pedicle subtraction osteotomy or closing wedge osteotomy (CWO). Anatomic limitation of 1 vertebral body restricts CWO to approximately 35° of lordosis at the osteotomized vertebra. Further movement often requires over 1 CWO to obtain adequate correction, but can also be achieved using COWO at a single level by fracturing the anterior vertebral cortex. The efficacy of COWO for the treatment of sagittal imbalance is unclear.

Methods. Eighty-three consecutive patients treated for sagittal imbalance with lumbar COWO with a minimum follow-up of 2 years were analyzed. Radiographic analysis included assessment of thoracic kyphosis, lumbar lordosis, lordosis through COWO site, sagittal translation at the site of osteotomy, and sagittal balance. Outcomes analysis used the Scoliosis Research Society questionnaire. Complications and radiographic findings were analyzed.

Results. The average increase in lordosis and improved sagittal balance were 81.9° and 17.1 cm. Mean correction through the osteotomy site was 42.2° (range, 31–55°). Sagittal translation occurred in 40% of these patients. No vascular injury occurred. Although 3 patients developed lumbosacral pseudarthrosis, the COWO area was unaffected in all patients. Nine patients developed cephalad junctional kyphosis and 2 patients developed caudad junctional kyphosis. Most patients reported improvement in terms of pain, self-image, and function as well as overall satisfaction with the procedure.

Conclusion. COWO is a useful procedure for patients with sagittal imbalance requiring more than 35° lordotic correction through the osteotomy site. A worse clinical result is associated with increasing patient comorbidities, pseudarthrosis in lumbosacral fusion, and junctional kyphosis.

Key words: closing-opening wedge osteotomy, closing wedge osteotomy, sagittal imbalance, sagittal translation. **Spine 2008;33:1470–1477**

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Symptomatic sagittal imbalance is prevalent in adult patients requiring spinal surgery.[1] Restoration of sagittal balance and pain reduction typically involves the Smith-Petersen, or open wedge, osteotomy (OWO) (Figure 1), or the pedicle subtraction, or closing wedge osteotomy (CWO) (Figure 2). OWO-mediated lordosis involves shortening of the posterior column and lengthening of the anterior column, with the middle column comprising a pivot. Anterior column lengthening can produce vascular injury.[2–4]

CWO (transpedicular wedge resection) permits correction through all 3 columns from a posterior approach without lengthening the anterior column, thereby maximizing the healing potential while avoiding stretch on the major vessels and viscera anterior to the spine, avoiding the risk of vascular injury. The anatomic limitation of the anterior cortex of 1 vertebral body restricts 1-level CWO to approximately 35° and 25° of lordosis in the lumbar and thoracic spine, respectively.[5] When sagittal imbalance requires greater correction at the CWO site, fracture of the anterior cortex of the vertebral body is necessary, which transforms a CWO into a closing-opening wedge osteotomy (COWO) (Figure 3).

Little if anything is known of the use of COWO in patients with coronal, axial, and sagittal deformities. Presently, we are describing a new technique and assessed the complications and radiographic/functional outcomes of COWO in patients with sagittal imbalance. Additionally, we examined the feasibility of performing 1 COWO rather than several CWOs to accomplish large correction for severe sagittal imbalances and complex deformities.

Materials and Methods

Medical records of 90 consecutive patients who underwent COWO for sagittal imbalance by the same surgeon from 2000 to 2004 were retrospectively reviewed. Two patients died of unrelated causes and 5 were lost to follow-up. The remaining 83 patients (52 women, 31 men, mean age of 66.1 years, range 52–76 years) were followed for 2 to 5 years.

Diagnoses included flatback syndrome with instrumented lumbar fusion (n = 14), degenerative kyphosis (n = 26), post-traumatic kyphosis (n = 13), iatrogenic kyphosis (n = 11), and ankylosing spondylitis kyphosis (n = 19).

Patients with the apex of kyphosis in the cord territory were excluded, as they were treated with apical lordosating osteotomy[6] to accomplish the large lordotic correction and prevent cord kinking.

Patient questionnaires were administered prospectively. Before surgery and at the time of the most recent follow-up, patients responded to the Scoliosis Research Society outcome

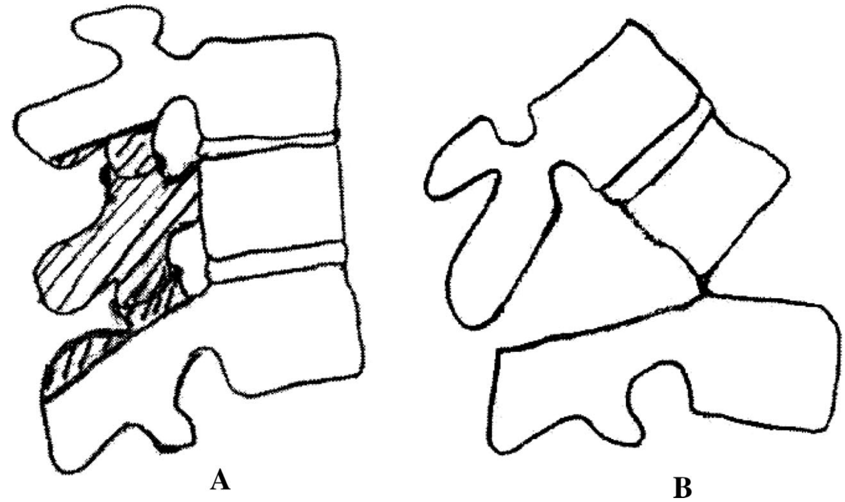

Figure 1. Diagrams of OWO. **A,** Lateral view outlining the bone block to be resected. Total pediculectomy avoids nerve root compression by the remaining pedicle because of sagittal rotation of the cranial vertebral column in OWO.[17] **B,** Postoperative lateral view showing that correction is achieved by hinging on the posterior border of vertebral body, closing the posterior osteotomy, and creating an open wedge of the anterior column.

questionnaire-24[7] regarding pain, self-image, function, and satisfaction. Intraoperative data included operative time and blood loss. Complications were also recorded.

Long-cassette standing anteroposterior and lateral radiographs were made before surgery, 2 months after surgery, and at the most recent postoperative visit. Lateral views of the spine obtained with the patient's hips and knees fully extended. The radiographs were made prospectively and then were reviewed retrospectively. The radiographs were analyzed to determine preoperative and postoperative fusion; osteotomy level; sagittal balance measured from the sagittal C7 plumb line to the posterosuperior corner of the S1 body; coronal balance measured from the coronal C7 plumb line to the center of the S1 body; sagittal Cobb angles between T5–T12 (thoracic kyphosis), T12–S1 (lumbar lordosis), between endplates of the osteotomized vertebra (COWO angle), and the Cobb angle of kyphotic deformity. Because the S1 body posterosuperior aspect was used as the sagittal balance reference point, the normal neutral range for this balance was considered to be 0 to 4 cm from this point (C7 plumb line running through the L5–S1 disc). Paired *t* tests were used for continuous variables between time-points. Statistical significance was set at $P < 0.05$. Sagittal translation (ST)[8] was determined by comparing preoperative and postoperative standing lateral radiographs. ST was any measurable displacement more than 2 mm between the posterior inferior edge of the cephalad portion of the osteomized vertebral body and the posterior superior edge of the caudad portion of the osteomized vertebral body.

For surgery, each patient was positioned prone with padding at the iliac crests, knees, shoulders, and chest. The abdomen was free to reduce intraoperative bleeding. The osteotomy site was over the hinge in the table; as the osteotomy was closed, the table could be moved from the neutral to the V position. A standard posterior midline incision was made (usually from proximal level identified as the stable, neural, and horizontal vertebra with a stable superjacent disc in the coronal and sagittal planes to the sacrum). The spine was bilaterally exposed to the tip of the transverse processes with a strictly subperiosteal approach to reduce bleeding. Pedicle screws were inserted into several segments cephalad and caudad to the osteotomy level.

Posterior decompression and lateral-recess decompression and foraminotomy of the involved stenotic levels were sometimes necessary to treat neurogenic claudication and pain.

Laminectomy and facetectomy at the level of osteotomy were done. After both pedicles to be resected were identified, holes were made through them to the vertebral body, and curettes were used to enlarge the holes. The transverse processes were excised at their bases. With angle curettes, the cancellous bone was pushed anteriorly into the body to create a cavity. The anterior, posterior, and lateral cortices of the body were thinned with angled curettes, and both pedicles were enucle-

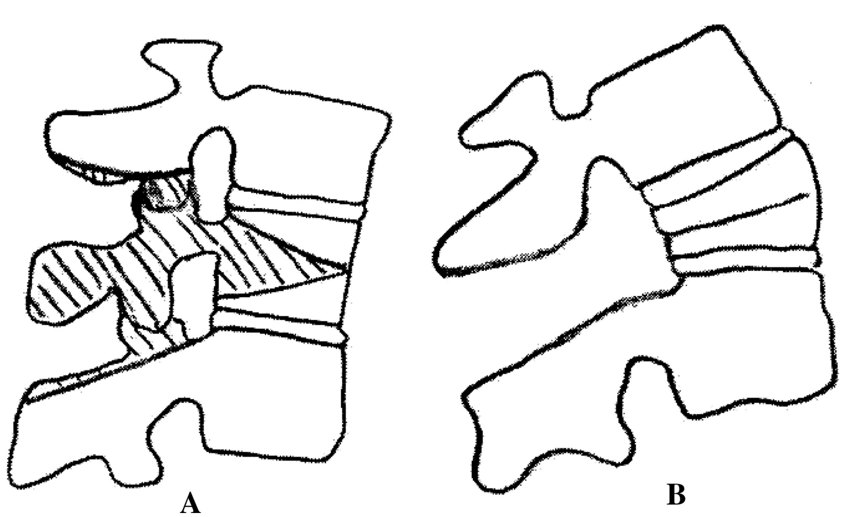

Figure 2. Diagram of CWO. **A,** Lateral view outlining the bone block to be resected. **B,** Postoperative lateral view showing that correction is achieved by hinging on the anterior cortex of the vertebral body and closing the intravertebral osteotomy.

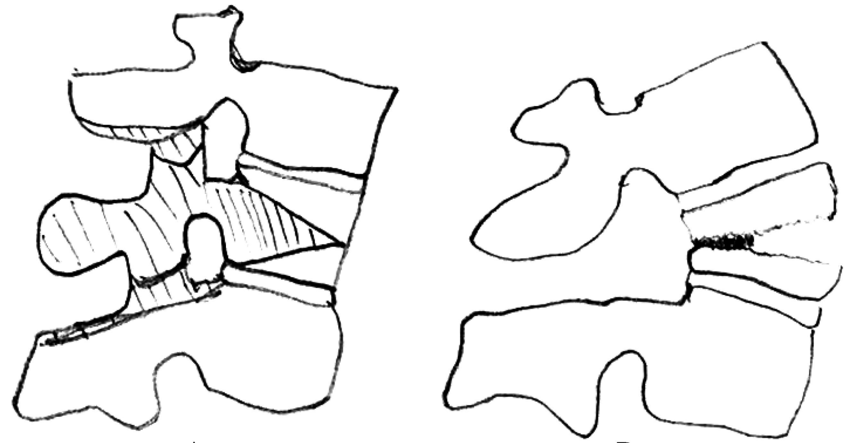

Figure 3. Diagram of COWO. **A,** Lateral view outlining the bone block to be resected. **B,** Postoperative view showing the correction is achieved by hinging on the closed middle column, closing the intravertebral osteotomy, and creating an open wedge of the anterior column.

ated with a small osteotome. The posterior cortex was then pushed down into the body. A rongeur was used to resect the appropriate lateral cortex bilaterally.

A prebent rod of appropriate lordosis was connected to the pedicle screws. The pedicle screws were Diapason long-arm screws. The ample space within the screw head and the flexibility of the rod allowed the rod with prebent lordosis to connect to the screw heads before the correction was achieved. The operating table was slowly moved to the V position to facilitate correction and provide space for lumbopelvic ST and rotation around the hip axis. The rod was rotated to correct any scoliosis and then pushed the rod at the site of osteotomy and compressed the pedicle screws immediately above and below the osteotomy to correct kyphotic deformity and create the lumbosacral lordosis.

The corrective procedures aimed for the best possible sagittal balance or alignment; restoration of the C7 sagittal plumb line falling within the L5–S1 disc for patients with global sagittal imbalance or sagittal alignment to normal for patients with regional sagittal imbalance (segmental hyperkyphosis). The sagittal balance and alignment was assessed on the operating table by intraoperative lateral radiographs. We initially preserved the anterior cortex of the body intact during closure of the osteotomy site. The anterior cortex at the level of COWO would be fractured and opened at this position by further pushing the lordotic rod at the site of osteotomy and compressing the pedicle screws immediately above and below the osteotomy if correction attempted by CWO was insufficient and if the anatomic limitations were exceeded to approximate the best possible sagittal balance; this was especially the case if the bone was osteoporotic. The fulcrum point during this opening was middle column. Following case 30, the anterior cortex was weakened by bilateral penetration with a blunt-end cage trial to facilitate its fracture and opening during corrective procedures for patients with sagittal imbalance requiring large magnitude of correction. We thus created a closing wedge of the posterior and middle columns and an opening wedge of the anterior column at the osteotomized vertebra.

Central and lateral bone-on-bone contacts were tightly closed. The correction was fixed with another rod and fused with autogenous bone grafts. The roots and dura were checked to exclude residual compression by centrally enlarging the canal. A Woodson elevator was passed up and down the canal through the area of central decompression to detect dorsal neural compression created by osteotomy closure. Wake-up tests were done during surgery.

The level of osteotomy was chosen on the basis of the location of the apex of kyphotic deformity. If there was no apex, such as flat back syndrome with instrumented lumbar fusion, preference was osteotomy caudad to the *conus medullaris* (below L1). COWO was performed at L2 in 58 patients and at L3 in 25 patients. All patients had only 1 osteotomy (Table 1).

Choosing the cranial limit of the fusion and instrumentation was based on factors thought to be important to the overall survival of spinal segments adjacent to a spinal fusion. These factors include starting with healthy adjacent segments with no degeneration or instability in any plane; stopping adjacent to spinal segments with normal sagittal, coronal, and axial alignment. Additionally, extending instrumentation to T10 or proximal may provide relative protection to the adjacent segment *via* increased stability afforded by the rib cage.

The arthrodesis was stopped at L5 in 26 patients in whom the L5–S1 disc appeared well preserved or was completely collapsed and stable. The arthrodesis was extended to S1 in the remaining patients. Iliac screws were used for all arthrodeses to the sacrum. Anterior bone grafts were not routinely used for segments added to the arthrodesis. However, interbody fusion with wedge-shaped cages placed from posteriorly for anterior-column support and fusion at L5–S1 were performed along with neurologic decompression procedures for 21 patients combined with spinal stenosis at L5–S1 because of the known difficulty of obtaining a long fusion to the sacrum.

Patients ambulated 48 hours later and used custom-made thoracolumbar orthoses for at least 6 months after surgery.

Table 1. Operative Time, Blood Loss and Number Level of Osteotomy and Number Osteotomy in 83 Patients With Sagittal Imbalance

Operative Data	
Operative time (min)	245 (191–313)
Estimated blood loss (mL)	3340 (2519–7160)
Level of osteotomy sites	
L2	58
L3	25
1 osteotomy	83
>1 osteotomy	0

Data are the mean (range).

Table 2. Summary of Complications

Complications	No. Patients (N = 41)
Perioperative death	0
Acute *cauda equina* syndrome	1
Wound infection	1
Congestive heart failure	2
Dura tear	3
Pneumonia	3
Paralytic ileus	15
Prominence of lilac screw	2
Cephalad junctional kyphosis	9
Caudad junctional kyphosis	2
Implant failure/pseudoarthrosis	3

■ Results

Surgical Outcomes

The mean estimated blood loss and operating time were 3340 mL (range, 2519–7160 mL) and 245 minutes (range, 191–313 minutes), respectively (Table 1). No perioperative deaths or vascular complications occurred. Three patients who developed postoperative pneumonia were successfully treated. One patient experienced acute *cauda equina* syndrome immediately after surgery. A computerized tomography myelogram showed a block at the level of osteotomy because of blood clot compression. Evacuation of the blood clot was performed the same day; neurologic recovery was complete. Two patients developed congestive heart failure, which resolved after medical management. One patient developed a superficial wound infection that was successfully debrided, closed, and treated with antibiotics. Fifteen patients developed paralytic ileus, which resolved after a Levin tube was inserted and oral intake restricted. Dural tear in 3 patients was repaired during surgery. Two patients complained of prominence of the iliac screws, which were subsequently removed. L5–S1 rod breakage with pseudarthrosis-mediated kyphosis that occurred in 3 patients was treated with anterior and posterior bone grafts. Nine of 83 patients developed progressive junctional kyphosis at the cephalad end of the construct. Three patients developed late compression fracture of the most cephalad vertebral body included in the construct, and another 3 patients developed a compression fracture immediately above the instrumented level; all resulted in kyphosis and loss of sagittal balance and required extension to the upper thoracic spine. Three patients did not have radiographic evidence of any compression fracture but became progressive kyphotic and required extension to the upper thoracic spine. Two patients with a long fusion to L5 developed caudad migration of the distal screw with some loss of sagittal correction. Revision surgery and improved sagittal balance were achieved using CWO and extension of the instrumentation to the sacrum (Table 2).

Radiographic Results

The average preoperative T1–T12 kyphosis was 25.9°. This increased to 29.2°, 2 months after surgery and to 31.8° at most recent follow-up. The average preoperative T12–S1 lordosis was 9.2°. The curve was corrected to −54.8° at 2 months after surgery, and to −51.3° at most recent follow-up. A normal sagittal alignment was reconstructed. Mean sagittal balance improved from 18.2 ± 8.9 cm before surgery to 1.1 ± 3.3 cm 2 months after surgery ($P < 0.01$). At the final postoperative visit, the mean sagittal balance increased to 4.7 ± 3.1 cm (P = 0.04 compared with the 2-month postoperative value). Loss of correction due to distal migration of the L5 pedicle screw was seen in 2 patients who had a fusion to L5. Loss of correction was also observed in 9 patients who had development of a cephalad junctional kyphosis. Substantial loss of correction also occurred in 3 patients who developed lumbosacral pseudarthrosis. Sagittal correction in the remaining 69 patients was maintained and there were no significant differences in the values between the 2-month and most recent postoperative visits. The mean correction through the osteotomy site was 42.2° (range, 31–55°) 2 months after surgery and 41° at the most recent follow-up. Mean correction of the kyphotic deformity was 81.9°. Half of the kyphosis correction was at the level of COWO. ST occurred in 33 of the 83 patients (40%). All the opening wedge gaps created in the anterior column obtained fusion (Table 3 and Figure 4).

Questionnaire Results

Eighty of the 83 patients completed the Scoliosis Research Society outcome questionnaire-24 questionnaire before surgery and at final follow-up (Table 4). With a higher score being indicative of a better result, the total and subset scores were: total score (120), postoperative score (final 9 questions 45), pain (25), self-image (25),

Table 3. Radiographic Data Summary

Measurement	Preoperative	Postoperative 2 mo	Last Follow-up	Correction	Loss of Correction
T1–T12 kyphosis (°)	25.9 ± 11.1	29.2 ± 16.8	31.8 ± 16.3	3.3 ± 3.1	3.5 ± 2.5
T12–S1 lordosis (°)	9.2 ± 3.2	−54.8 ± 16.8	−51.3 ± 17.1	64 ± 21.4*	3.5 ± 3.3
Kyphosis (°)	66.5 ± 17.4	−15.4 ± 4.7	−13.7 ± 4.5	81.9 ± 21.5*	1.7 ± 2.1
Sagittal balance (cm)	18.2 ± 8.9	1.1 ± 3.3	4.7 ± 3.1	17.1 ± 7.8*	3.6 ± 3.3*
Coronal balance (cm)	4.1 ± 1.1	1.5 ± 1.7	1.3 ± 1.1	2.6 ± 1.3*	0.2 ± 1.3
COWO angle (°)	12.1 ± 7.2	−30.1 ± 13.2	−28.9 ± 14.1	42.2 ± 19.1*	1.2 ± 1.9

Data are mean [plusmn] standard deviation.
*$P < 0.05$.
COWO indicates closing-opening wedge osteotomy.

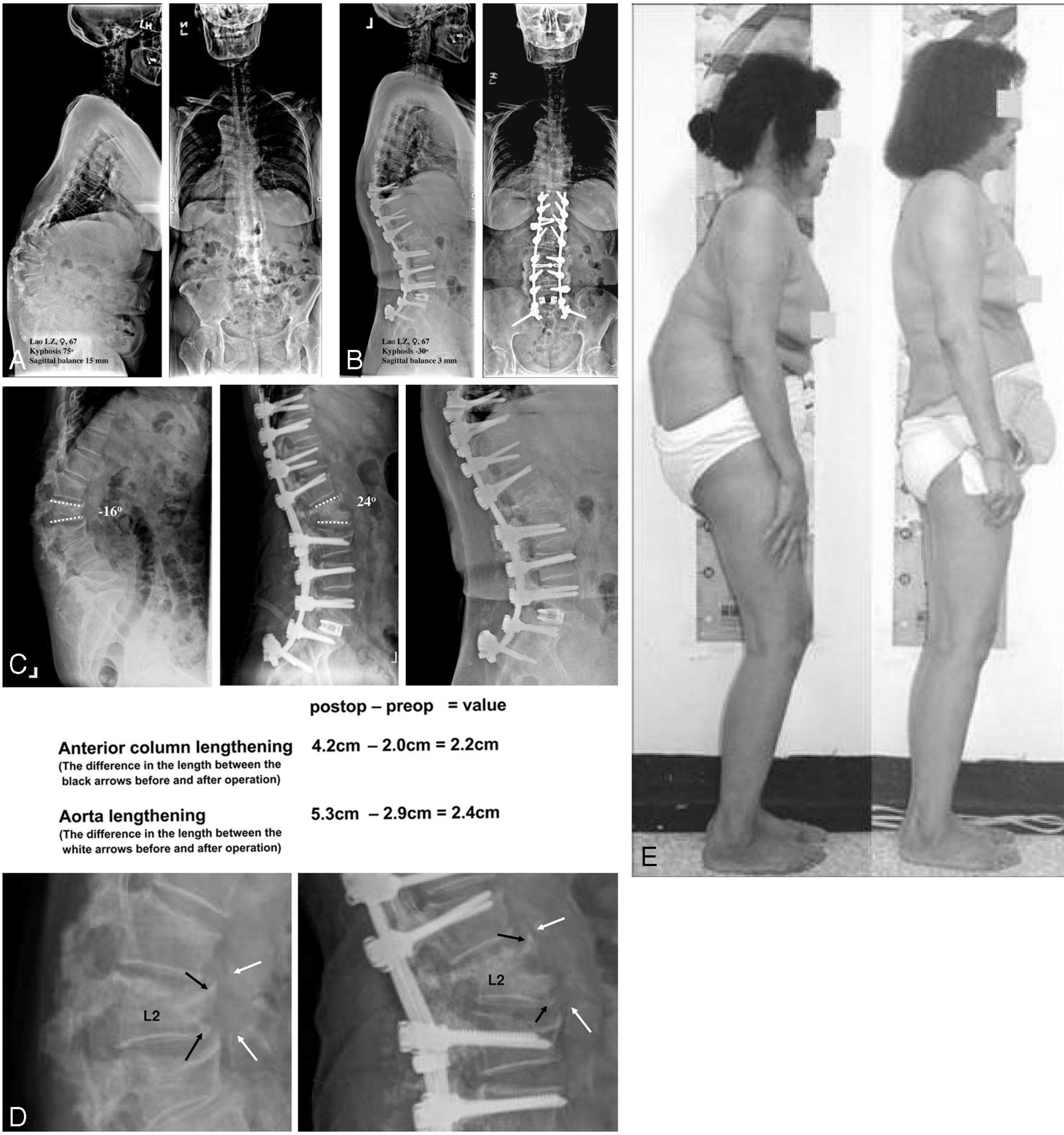

Figure 4. A representative example. A 67-year-old woman with iatrogenic kyphosis (kyphosis after laminectomy). **A,** Presurgical image showing 75° kyphosis, 15 cm sagittal balance, and 61° T12–S1 lordosis. **B,** Final values were −30° kyphosis, 3 cm sagittal balance, and −55° T12–S1 lordosis. The patient was pain free and extremely satisfied with the outcome. **C,** The correction through the osteotomy site was 40°. Sagittal translation joined the mechanism of correction. The anterior open wedge obtained solid fusion. **D,** The magnitude of aorta lengthening at the level of osteotomy was 2.4 cm, as determined by measuring the difference in the length between the same athermatous calcification marks exactly in front of the osteotomized vertebra seen roentgenographically in the aorta before and after operation. The aorta tolerated the lengthening very well. **E,** Preoperative and ultimate appearances. Please note, the thoracic spine was lordotic before operation and T10 was not the apex of thoracic curve before surgery. The lordotic thoracic curve was corrected to a normal kyphotic curve by posterior pull of the instrumented low thoracic spine and thus T10 became the apex of the thoracic kyphosis after surgery. Indeed, this is known to predispose to junctional problems. However, from a clinical perspective, the postoperative sagittal balance seems to be the most critical factor in the patient's clinical outcome. Up to now, no junctional problems occur in this case.

and function (25). Domain scores were significantly improved for pain ($P < 0.01$), self-image ($P < 0.01$), and function ($P = 0.03$). On the basis of the last 9 questionnaires, reported detrimental aspects of spine treatment included reduced function and daily activity (n = 15), reduced ability to participate in sports and hobbies (n = 19), and increased back pain (n = 8). Of the latter 8 patients, the pain was due to implant failure and

Table 4. SRS Outcome Instrument Paired Scores (N = 80)

	Mean at Preoperative	Mean at Final Follow-up	P (Preoperative to Final Follow-up)
Total scores (120 possible) SRS domain	34.2 ± 9.5	98.6 ± 17.4	—
Pain (25 possible)	10.5 ± 3.5	20.8 ± 6.1	<0.01
Self-image (25 possible)	11.3 ± 4.7	22.3 ± 6.3	<0.01
Function (25 possible)	12.4 ± 5.41	17.3 ± 5.0	0.03
Satisfaction (45 possible)	—	38.2 ± 8.1	—

Values are expressed as mean ± standard deviation. $P < 0.05$ is statistically significant. Total and subset scores were: total score (120), pain (25), self-image (25), function (25), and postoperative score (last 9 questions, 45). Last 9 included the satisfaction scores and are represented as satisfaction.

pseudarthrosis at L5–S1 (n = 2), caudad junctional kyphosis (n = 2), cephalad junctional kyphosis (n = 3), and metastatic prostate cancer (n = 1). In contrast, 71 patients believed that the spine treatment had improved their confidence and personal relationships with others. Reported benefits included improved perception by others (n = 70), better self-image (n = 67), and improved personal appearance (n = 75). The overall satisfaction scores (questions 22 and 24) were high. Seventy-two of the 80 patients were "satisfied" with the treatment, 6 were ambivalent, 1 was somewhat dissatisfied, and 1 was extremely dissatisfied. Seventy-one of the 80 patients would have the treatment again, 7 were not sure, 1 probably would not, and 1 definitely would not. The 2 patients who were dissatisfied with the treatment would also not seek treatment again. One developed postoperative congestive heart failure and the other developed metastatic prostate cancer.

■ Discussion

The present study analyzed the clinical and radiographic results for patients undergoing COWO for sagittal deformity. To our knowledge, the present study represents the largest series of patients with sagittal deformity who have been managed with COWO.

Patients with sagittal imbalance cannot stand erect without compensatory hip extension, knee flexion, and overwork of the erector spinal musculature because reduced moment arm compromises the mechanical advantage. The result is muscle fatigue and activity-related pain. As patients age, muscular weakness, adjacent disc degeneration, and hip and pelvic disease may decrease compensation and increase disability. Restoration of normal and economical sagittal balance reduces the work of the spinae erecta and hamstring muscles to achieve balance during normal activity.

The spine should be fused in a balanced position that is as close to the normal configuration as possible because insufficient deformity correction involving posterior instrumentation alone may lead to lost correction, pseudarthrosis, increased reoperation rates, or poor clinical results.[9,10] CWO can provide acceptable clinical and radiographic results for patients with sagittal imbalance.[10] However, anatomic limitation of a vertebral body restricts CWO to about 35° lordosis.[5,11,12] When sagittal imbalance exceeds 25 cm, consideration should be given to performing more than just 1 CWO to obtain adequate correction,[13] increasing the risks and complications of the surgery. In our present and previous[14] studies, higher correction was achieved with COWO by fracturing the anterior vertebral cortex. This avoids the necessity for another osteotomy at another site. The prevalence of satisfactory results highlights the utility of COWO to surgically treat sagittal imbalances that require large correction. The technique is a 3-column release that makes a rigid deformity flexible enough to be adequately manipulated from behind to obtain optimal correction.

COWO shortens the posterior and middle spinal columns. Many believe excessive shortening is dangerous; limiting corrections to approximately 30 to 40° has been recommended.[13] If kyphotic correction exceeds 40° with spine shortening, the spinal cord may be too long for the shortened column, resulting in curving, kinking, or damage.[15] Correction at any level for posterior transvertebral osteotomy should not exceed approximately 35°.[12] For transpedicular wedge resection osteotomy, correction of a sagittal deformity should be below L1 and of a magnitude correctable with a closing wedge <45°.[16] Many patients in our current and previous[14] studies achieved correction of over 45° without neurologic complications, demonstrating the safety of closing wedge below L1 as well as the tolerance of *cauda equina*. Redundant *cauda equina* may not be problematic if enough bone is removed to accommodate the excess neural tissue.

It is generally believed that in elderly patients anterior column lengthening at a single level by OWO carries a risk of elongating the tethered aorta or calcific nondistensible aorta, which could prove disastrous. However, no aorta injury occurred in this study. Aorta injury has been reported if the opening wedge is performed at L1–L2 or L2–L3.[2–4] Reviewing these reports and postmortem findings reveals 2 cases of rheumatoid spondylitis treated before surgery with radiograph therapy, in which adherence between the aorta and the underlying anterior longitudinal ligament resulted in a complete transverse tear in the posterior wall of the aorta after manual osteoclasis and nonsurgical or surgical correction.[2,3] Such preoperative therapy was not conducted presently. We did not find any reference in the literature that the presently observed etiologies are linked to aortic-longitudinal ligament adherence. In the other 2 cases involving ankylosing spondylitis kyphotic patients with atheromatous calcification of their abdominal aorta,[4] the vascular injuries involved OWO-related aortic wall tear and dissection of media. Stretching of calcific nondistensible aorta that created internal and media tears may have led to rupture and aneurysms. However, based on our observations of the absence of aortic injury in 354 patients treated with OWO including 101 patients with atheromatous calcification of abdominal aorta, apical lordosation osteotomy,[6] or COWO for correction of sagittal imbalance or kyphosis *via* an anterior open wedge and lengthening of the anterior column, the aorta can likely tolerate stretch and lengthening very well, even when complicated by atheromatous calcification (Chang KW, Chen YY, Lin CC, *et al*, unpublished data, 2007) Aorta lengthening was measured at the level of osteotomy in 49 patients who displayed roentgenographically-obvious atheromatous calcification marks exactly opposite the site of osteotomy in the aorta, by comparison of the preoperative and postoperative lengths between the same atheromatous calcification marks. The mean aorta lengthening at the level of osteotomy was 2.8 cm (range, 1.7–3.5 cm) (Chang KW, Chen YY, Lin CC, *et al*, unpublished data, 2007) (Figure 4D).

ST effectively improves sagittal balance; a few millimeters of hinge displacement may achieve a few centimeters of correction. Previously, we have demonstrated that ST is one of the basic mechanism for correction of sagittal imbalance in ankylosing spondylitis by OWO.[8] Similar to OWO, COWO procedures involve 3-column release and unrestricted movement of the hinge of correction, which can produce ST. ST occurred in 40% of these patients. Patients who need more correction of lumbar lordosis than others to approximate the best possible correction of sagittal imbalance also need more ST to join the mechanism of correction. The correction of sagittal imbalance by COWO was accomplished by shortening of posterior and middle columns and opening of the anterior column with or without ST.

ST poses a risk of neurologic complications because of displacement and rotation of the osteomized vertebral body. Compression of a dorsal nerve root by lamina or pedicle can result from closure of the osteotomy and ST. Total pediculectomy and enough lamina should be removed to prevent this complication. ST subjects the great vessels to an anteriorly directed force in addition to stretch. In the presence of ST, spike formation at the anterior edges of the open wedge might result in a stabbing injury of the tensed great vessels. However, during the corrective procedures of COWO, the thin anterior cortex of the osteomized vertebral body fractured in a green stick manner, and opened with smooth edges and without spike formation. Accordingly, no spike was found and no vascular injury occurred in these patients.

Presently, we observed that paralytic ileus increased with COWO, perhaps in association with elongation of the lumbar anterior column, caused tension on the anterior abdominal organs. All cases resolved with gastric-tube decompression. One of the concepts behind the COWO procedure is that surgery on all 3 columns is performed through a posterior approach and a gap is created in the anterior column. Our observations indicate that anterior grafting is not required. All the anterior open wedges obtained solid fusion. Osteoclasis and rigid fixation may mimic a close fracture with rigid fixation, which always produces solid union of a fracture. No substantial loss of correction through the site of COWO was apparent.

Presently, cephalad junctional kyphosis (n = 9) and caudad junctional kyphosis (n = 2) resulted in significant loss of sagittal balance. All required reoperation for progressive junctional kyphosis, which may be an inevitable consequence of multilevel instrumentation in patients with poor bone stock.[17] A potential approach to this problem is to perform limited fusion with the intention of staging proximal extension as the junctional kyphosis progresses. Increased motion and stress concentration at this junctional area can induce instrumentation failure and adjacent segment problems, leading to junctional kyphosis. Long-term follow-up of large, well matched adult deformity cohorts will be required to determine the impact that the factors have on adjacent segment survival. There may be other reasons why the present incidence of junctional kyphosis was so high. A group of patients presented with lumbar kyphosis and many had substantial positive sagittal balance. Given the long-standing nature of their deformities, these patients might have equilibrated to a more forward-flexed position and, therefore, continued to stand in this familiar, stooped posture, despite the local change in lumbosacral lordosis achieved during the instrumented reconstruction. This would suggest a role for some, as yet unidentified neurologic or proprioceptive mechanism that contributes to an individual's ability to maintain a neural sagittal balance. Undoubtedly, the severe reconditioning of the lumbar paraspinal musculature that occurred as the result of the posterior exposure influenced the patients' ability to stand erect.

Three-rod breakage with subsequent kyphosis occurred at L5–S1 in some patients in the absence of pullout or breakage of S1 screws. For long fusions to the sacrum, a montage of bilateral S1 and iliac screws effectively protected the sacral screws. Nonetheless, pseudarthrosis occurred at L5–S1, which unexpectedly manifested as rod breakage on both sides. Anterior-column support and anterior bone grafting reduced but did not eliminate the complication. So, it was not our routine practice to perform structural grafting at L5–S1 through the anterior approach. We used high concentrations of autogenous bone anteriorly and posteriorly to treat pseudarthrosis after its occurrence.

In conclusion, we believe that COWO can provide acceptable clinical and radiographic results for patients who have had sagittal imbalance requiring a large magnitude of correction. The operative times in the present study were reasonable, but some patients lost a substantial amount of blood. Complications were seen in approximately 49% of the patients. Pseudarthrosis and loss of correction at the level of COWO was not observed. However, lumbosacral pseudarthrosis and junctional kyphosis were problematic. Although anterior column lengthening at the osteotomized level by COWO elongated the stiff aorta in elderly patients, the aorta seemed to tolerate the lengthening very well and no vascular injury occurred. The level of patient satisfaction was high after more than 2 years of follow-up, with most patients having improved resolution of pain, increased self-image, and greater function. A worse clinical result was associated with junctional kyphosis, lumbosacral pseudarthrosis, and increasing patient comorbidities.

■ Key Points

- Closing-opening wedge osteotomy is highly effective in correcting sagittal imbalance requiring more than 35° lordotic correction at the osteotomized level.
- A worse clinical result is associated with cephalad and caudad junctional kyphosis, lumbosacral pseudarthrosis, and increasing patient comorbidities.
- Aorta tolerance of lengthening at the level of osteotomy was exceptional, even with atheromatous calcification. No vascular injury occurred.

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