

The Value of Cement Augmentation in Patients With Diminished Bone Quality Undergoing Thoracolumbar Fusion Surgery: A Review

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Abstract

Study Design: Systematic review.

Objectives: Osteoporosis predisposes patients undergoing thoracolumbar (TL) fusion to complications and revision surgery. Cement augmentation (CA) improves fixation of pedicle screws to reduce these complications. The goal of this study was to determine the value and cost-effectiveness of CA in TL fusion surgery.

Methods: A systematic literature review was performed using an electronic database search to identify articles discussing the cost or value of CA. As limited information was available, the review was expanded to determine the mean cost of primary TL fusion, revision TL fusion, and the prevalence of revision TL fusion to determine the decrease of revision surgery necessary to make CA cost-effective.

Results: Two studies were identified discussing the cost and value of CA. The mean cost of CA for two vertebral levels was \$10 508, while primary TL fusion was \$87 346 and revision TL fusion was \$76 825. Using a mean revision rate of 15.4%, the use of CA for TL fusion would need to decrease revision rates by 13.7% to be cost-effective. Comparison studies showed a decreased revision rate of 11.3% with CA, which approaches this value.

Conclusion: CA for TL fusion surgery improves biomechanical fixation of pedicle screws and decreases complications and revision surgery in patients with diminished bone quality. The costs of CA are substantial and reported decreases in revision rates approach but do not reach the calculated value to be a cost-effective technique. Future studies will need to focus on the optimal CA technique to decrease complications, revisions, and costs.

Keywords

adult spinal deformity, cement augmentation, vertebroplasty, complications, cost, kyphoplasty, spine augmentation, osteoporosis

Introduction

Osteoporosis remains the most prevalent bone disorder in the world and estimates have shown up to 20% of men and 50% of women will have an osteoporosis-related fracture.¹ Although there have been major advances in the diagnosis and treatment of this disease, osteoporosis and bone health care remains sub-optimal.² As such, osteoporosis and bone quality are important factors for all spine surgeons to consider when planning thoracolumbar (TL) fusion surgery.³

Previous studies have shown 41% to 59% of patients undergoing spinal surgery have osteopenia and 10% to 51% have osteoporosis.^{4,5} Diminished bone mineral density (BMD) has been shown to be a risk factor for a variety of complications in spine

surgery, including vertebral body compression fractures (VBCF), proximal junctional kyphosis (PJK), proximal junctional failure (PJF), hardware failure (broken or dissociated arthrodesis components, screw pull-out, or screw loosening), pseudoarthrosis, and catastrophic failure.^{5,6} This has led to a variety of treatment options to help reduce these complications, including

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preoperative optimization with treatment of osteoporosis with bisphosphonates and other anabolic medications and vitamin D deficiency with supplementation.^{3,7} Similarly, improved surgical techniques such as the use of nontraditional screw trajectory, untapping of screws, new hardware designs, the use of anterior column support, and cement augmentation (CA) have been described to reduce complications in these patients.^{3,8}

A variety of techniques have been described for CA of pedicle screws. These include (1) transpedicular vertebroplasty augmentation, where cement is injected into the vertebral body through the pedicle and screws are inserted after cement injection⁹⁻¹¹; (2) kyphoplasty augmentation, where a cavity is created in the vertebral body using the inflatable bone tamp, cement is then injected down the pedicle path and screws are inserted after cementing¹²; (3) coating of pedicle screws with cement prior to insertion rather than injection of cement down the pedicle tract¹³; (4) use of cannulated screws with injection of cement through the cannulation after screw insertion¹⁴⁻¹⁶; and (5) vertebroplasty completed at a second stage after TL fusion. The best technique remains controversial as comparative studies have been conflicting.^{12,15,17,18} Therefore, the technique is often based on surgeon preference and availability of resources. Similarly, the levels to augment are often patient specific based on surgeon experience and size of the planned fusion construct.

In addition to its association with postoperative complications, BMD has been shown to correlate with pedicle screw stability.¹⁹⁻²¹ Many authors have determined CA can increase screw pull-out strength (POS) by 80-1031% in osteoporotic spines.^{15,17,22} Biomechanical studies have demonstrated improved POS with a kyphoplasty technique,¹² vertebroplasty-augmented solid screws,¹⁷ cement prefilling compared with cannulated screws,¹⁵ solid-core screws with cement prefilling,¹⁸ and partially cannulated fenestrated screws.²³ Additionally, cadaveric biomechanical testing has shown the use of prophylactic vertebroplasty at the upper instrumented vertebra (UIV) and cranial-adjacent vertebra (UIV+1) can help reduce the incidence of junctional fractures after long segment fusion.²⁴

Along with improved biomechanical fixation, CA has shown promising clinical benefits. These include improvements in walking distance, back pain, ability to perform activities of daily living, and Oswestry Disability Index scores,^{9,11} low incidence of osteoporosis-related complications (ORC) requiring revision surgery,^{9,11,25} sustained correction,¹¹ with no significant complications from cement leakage.²⁵ Clinical studies have also shown benefit when combining CA of pedicle screws with CA of the UIV+1 or the level caudal to instrumentation (LIV-1). These benefits include improvements in patient-reported outcomes,²⁶ a low incidence of complications from cement,²⁷ and low early incidence of ORC and revision surgery.^{26,27} However, studies with longer follow-up revealed moderate rates of ORC and revision surgery.²⁸ A recent meta-analysis reviewing screw-related complications in patients with osteoporosis found screw loosening was lower in CA screws (23% vs 2%) while fusion rates were higher (98% vs 88%) but this did not necessarily lead to an decreased risk of vertebral

fracture (7% vs 8%) or reoperation (4% vs 5%) compared with nonaugmented screws.²¹

A variety of techniques for CA of pedicle screws have been described to improve fixation in patients with poor bone quality with excellent results. Unfortunately, there is limited data examining the cost and value of this treatment method. The purpose of this review was to review the currently available literature on the value of CA, TL fusion, revision TL surgery, and the prevalence of revision surgery to perform a cost analysis of the use of CA in TL fusion surgery.

Methods

An electronic literature search was completed in March of 2020 including the PubMed, Cochrane, MedLine, and Google Scholar databases (Figure 1A). Search keywords included a combination of “cost,” “value,” “augmentation,” “spine,” and “pedicle.” Only literatures with abstract in the English language were included for review. These searches resulted in 138 articles of which the title and abstract were examined to ensure the study was relevant to our clinical question. “Is cement augmentation of pedicle screws a cost-effective technique to prevent revision surgery in patients with diminished bone density undergoing thoracolumbar spine surgery?” Full manuscripts of all relevant articles were then reviewed and only studies that included the cost or a cost analysis were included. Only two studies evaluated the cost of CA in patients undergoing TL fusions.^{29,30} One of these studies used CA of the vertebral bodies above the fusion construct rather than CA of pedicle screws, but was included given the low number of studies examining the value and cost of this technique.³⁰

As the primary literature was insufficient to complete a thorough value analysis of CA of pedicle screws, a review of the literature to examine cost of TL surgery, TL revision surgery, and the need for revision after TL surgery with and without CA of pedicle screws was completed. Search keywords included a combination of “cost,” “value,” “adult spinal deformity,” “revision,” “augmentation,” “spine,” and “pedicle” (Figure 1B). The mean cost of TL surgery and TL revision surgery reported in the literature was calculated. Similarly, the mean need for revision after long construct TL fusion was calculated.

We then used the following equation to determine the decrease in revisions necessary to make CA of pedicle screws cost-effective, $\$TLF + \$RTL F(\%R) = \$TLFCA + \$RTL F(x)$, ($\$TLF$, mean cost for TL fusion; $\$RTL F$, mean cost of revision TL fusion; $\%R$, mean percentage of need for revision; $\$TLFCA$, mean cost of TL fusion with CA; x , variable to solve for to determine the revision percentage in patients undergoing CA to make CA cost-effective). For this analysis we used the cost per vertebral level of CA from our literature review for 2 vertebral levels as many studies have shown good results with CA of only the UIV and level proximal to the fusion construct (UIV+1).^{26,28,31,32}

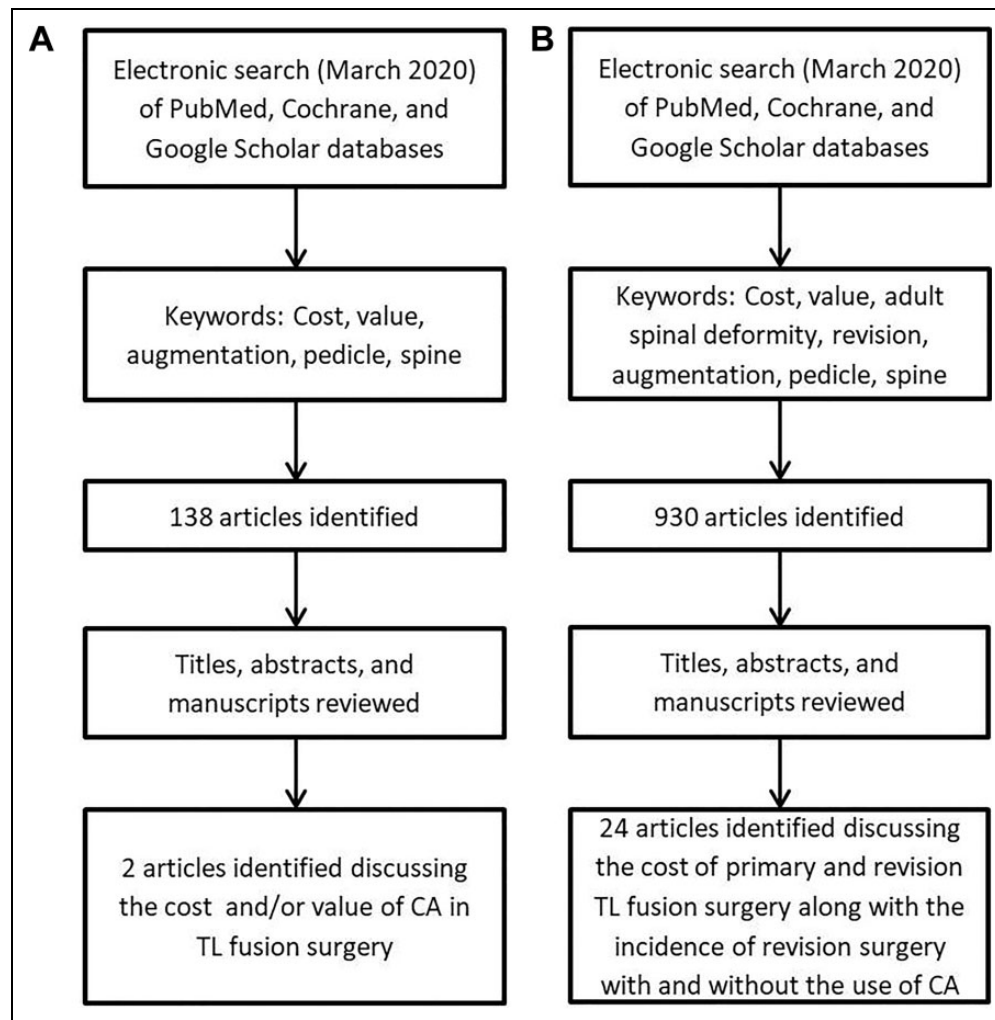


Figure 1. Flowchart of database search and article selection algorithm. Original literature search to evaluate the cost and value of cement augmentation (CA) (A) and the expanded literature search to determine the cost of thoracolumbar (TL) fusion, revision TL fusion, and the incidence of revision surgery for patients undergoing TL fusion with and without CA.

Results

The use of CA in spine surgery is becoming increasingly more common with 80% of German surgeons utilizing this technique routinely.³³ Surgeons are aware of the increased costs, but the value of this technique remains unknown. While the true cost for this technique and cost-effectiveness remains unknown, 2 studies have discussed the cost of CA.^{29,30}

Xie et al²⁹ examined the cost of CA of pedicle screws with polymethylmethacrylate (PMMA) (14 patients) compared with pedicle screws augmented with autograft bone (17 patients). They found the total treatment cost of CA with PMMA was \$157 899 while autograft augmentation cost \$121 722 (Table 1), a difference of \$36 177. This increased cost was attributed to the CA technique and PMMA as there was no difference in the number of level fused ($n = 6$), hospital length of stay or surgical time. No patients underwent revision at a mean 3.8 years. There was no difference in preoperative patient characteristics, complications, coronal or sagittal parameters, Oswestry

Disability Index, surgical times, or blood loss; however patients with PMMA augmentation did take opioid pain medications for a shorter period of time (6 vs 13 days, $P = .001$).²⁹ Due to the low numbers compared and lack of revision surgeries it is difficult to determine the value of CA from this study alone.

Hart et al³⁰ reviewed the cost of prophylactic vertebral augmentation of the 2 or 3 vertebral levels above a long-segment TL fusion construct. They reviewed 28 patients of which 15 underwent vertebroplasty or kyphoplasty cranial to the fused segment. They found the cost for an intraoperative 2-level vertebroplasty was \$6936 and kyphoplasty was \$12326 while the cost for revision surgery for proximal junctional collapse was \$77432. They reported a revision rate of 0% in patients receiving prophylactic CA and 15% in those without. Their analysis determined the cost to prevent a single proximal junctional acute collapse was \$46240 using vertebroplasty (must decrease incidence by 9%) and \$82172 using kyphoplasty (must reduce incidence by

Table 1. Mean Cost of Thoracolumbar Fusion, Revision Thoracolumbar Fusion, and Cement Augmentation Reported in the Literature.

Author (reason for revision/type of cement augmentation)	Cost per level, \$
Primary thoracolumbar fusion	
Theologis et al ³⁴	68 249
Xie et al ²⁹	121 722
Jain et al ³⁵	55 000
Varshneya et al ³⁶	85 190
Neal et al ³⁷	82 731
McCarthy et al ³⁸	75 117
Raman et al ³⁹	123 411
Mean	87 346
Revision thoracolumbar fusion	
Theologis et al ³⁴ (all)	55 547
Hart et al ³⁰ (PJF)	77 432
Jain et al ³⁵ (pseudarthrosis)	84 985
Jain et al ³⁵ (PJK)	67 420
Yeramaneni et al ⁴⁰ (pseudarthrosis)	92 755
Yeramaneni et al ⁴⁰ (PJK)	66 713
McCarthy et al ³⁸ (all)	67 220
Raman et al ³⁹ (all)	102 529
Mean	76 825
Cement augmentation	
Xie et al ²⁹ (IV)	36 177 (6132)
Hart et al ³⁰ (kyphoplasty)	12 326 (6163)
Hart et al ³⁰ (vertebroplasty)	6936 (3468)
Mean	18 480 (5254)

Abbreviations: PJF, proximal junctional failure; PJK, proximal junctional kyphosis; IV, instrumented vertebra.

16%).³⁰ This would appear to favor vertebroplasty in this scenario.

Neither of the above articles completely answers the question of what is the cost and value of CA of pedicle screws. Therefore, a combination of the above data and published data regarding the cost of primary TL fusion, revision TL fusion, and revision rates (Table 2) was used to perform a value analysis. The average cost for primary TL fusion found in the literature was \$87 346, cost of revision TL fusion was \$76 825, and cost for CA of 2 vertebral levels was \$10 508. There was a wide range of revision rates reported for long TL fusions (9%-21%), with an average rate of 15.4%.^{13,30-32,34,41-45} Value analysis determined, the use of CA for TL fusion would need to decrease revision rates by 13.7% bringing the total revision rate to 1.7% in order to be cost-effective.

Four studies have directly compared revision surgery for those undergoing CA and those without augmentation (Table 2). As previously discussed, Hart et al³⁰ found a revision rate of 15% in those not receiving CA and 0% in those undergoing prophylactic CA. Sawakami et al¹³ compared patients receiving CA and those without CA undergoing pedicle screw fixation for vertebral pseudarthrosis after an osteoporotic VBCF. They demonstrated a decreased incidence of clear zones around the screws in those receiving CA (29% vs 71%, $P < .05$) along with decreased loss of correction (3° vs 7°, $P < .05$) and increased fusion rates (94% vs 76%, $P < .05$).

There were no perioperative complications related to CA or cases of screw pull out. However, the rate of subsequent VBCF at an adjacent level was 30% with 12% requiring extension of the construct in the CA cohort compared to a VBCF rate of 24% and revision rate of 10% in the control group.¹³ Ghobrial et al³¹ showed vertebroplasty at the UIV and UIV+1 levels decreases PJK (24% vs 36%, $P = .02$), UIV+1 angle (6.8° vs 10°, $P = .02$) and PJF requiring revision (0% vs 13%, $P = .03$). Similarly, Theologis et al³² demonstrated that CA of the UIV and UIV+1 decreased adjacent fracture rate (5% vs 22%, odds ratio [OR] 3.7, $P = .19$) and need for revision (0% vs 19%, $P = .02$, OR 9.2, $P = .18$). The combined revision rate of these comparative studies was 3% for CA and 14.3% without CA.^{13,30-32} This indicates a decreased revision rate of 11.3%, which approaches the 13.7% calculated to make CA a cost-effective technique.

Discussion

ORCs remain a global concern for spine surgeons when considering TL fusion surgery. A variety of strategies have been used to improve pedicle screw fixation in patients with diminished bone density, including CA. Biomechanical studies have clearly demonstrated improved fixation of pedicle screws with CA.^{12,15,17,18,22,24} Similarly, many clinical reviews have shown lower complication rates and/or revision rates using CA.^{13,30-32} These studies demonstrate the importance of this technique to help limit ORC, unfortunately, the value and cost analysis of using this technique remains unknown. The goal of this review was to determine the value of CA in TL fusion surgery.

Many authors have previously evaluated the value of spine surgery. The surgical treatment of spinal stenosis,⁴⁶ adult spinal deformity surgery,⁴⁷⁻⁴⁹ and the use of rhBMP-2 (recombinant human bone morphogenetic protein-2)³⁵ have all been found to be cost-effective options. However, only 2 studies have discussed cost of CA in TL fusion surgery. Xie et al²⁹ found CA cost \$36 177 more than autograft augmentation of pedicle screws without changing the prevalence of revision surgery. Meanwhile, prophylactic CA of 2 segments above a fusion construct would need to decrease revision rates by 9% to 16% to be cost-effective.³⁰ Using our value analysis algorithm, we determined CA (of 2 vertebral segments) would need to decrease revision rates by 13.7% or more to be a cost-effective strategy. Review of comparative studies in the literature showed the use of CA decreases revision rates by 11.3%, which approaches but does not reach our calculated value needed to be cost-effective.

This value analysis has multiple limitations. There was limited primary data evaluating the cost-effectiveness of CA. Therefore, we expanded the review and used a cost-effectiveness formula to determine if CA was cost-effective based on available literature. This type of analysis is therefore restricted by the limitations of the studies included. While reviewing the cost of TL fusion and revision surgery there was a wide range of values. This is likely due to different payers being included in the cost analysis and differences in cost

Table 2. Complications and Need for Revision in Patients Undergoing Cement Augmentation for Thoracolumbar Fusion Surgery.^a

Authors	Levels of CA	Follow-up, mo, mean (range)	No. of patients with CA (no. of control patients)	Cement leakage	ORC (control)	ORC description	Need for revision	Reason(s) for revision
Chang et al ¹¹	IV	22 (4-35)	41	26%	2%	VBCF	NR	NA
Aydogan et al ²⁷	IV, UIV+1 LIV-1	37 (24-48)	36	3% (PE)	3%	Screw loosening	NR	NA
Sawakami et al¹³	IV	31 (24-82)	17 (21)	0%	36% (48%)	VBCF, pseudarthrosis	12% (10%)	Extension of construct for ORC
Wenger et al ⁹	IV	28 (1-84)	8	NR	NR	NA	13%	Instability
Martin et al ²⁶	UIV UIV+1	32 (24-48)	38	5% (5% PE)	21%	PJK, PJF, pseudarthrosis, sacral stress fracture	11%	PJF, pseudarthrosis, sacral stress fracture
Raman et al ²⁸	UIV UIV+1	66 (minimum 60)	39	5% (5% PE)	46%	PJK, PJF, pseudarthrosis, sacral stress fracture, VBCF, screw loosening	15%	PJF, PJK, pseudarthrosis, sacral stress fracture
Ghobrial et al³¹	UIV	25	38 (47)	NR	24% (36%)	PJK	0% (13%)	PJF
Theologis et al³²	UIV	15 (6-32)	19 (32)	NR	5% (22%)	VBCF	0% (19%)	PJF
Abousayed et al ²⁵	IV	25 (8-30)	25	20%	0%	NA	0%	NA
Xie et al ²⁹	IV	46 (24-91)	14	14%	0%	NA	0%	NA
Hart et al³⁰	UIV+1	17 (12-44)	15 (13)	NR	13% (23%)	VBCF, PJF	0% (15.3%)	PJF
	UIV+2							

Abbreviations: IV, instrumented vertebra; UIV+1, vertebra cranial to upper instrumented vertebra; UIV+2, second vertebra proximal to upper instrumented vertebra; LIV-1, vertebra caudal to lowest instrumented vertebra; NR, not recorded in study; NA, not available; ORC, osteoporosis-related complication; ASVBCF, adjacent segment vertebral body compression fracture; PJK, proximal junctional kyphosis; PJF, proximal junctional failure; CA, cement augmentation.

^a Boldfaced entries indicate comparative studies comparing CA during TL fusion with control TL fusion without CA.

between hospitals and regions.⁵⁰ Similarly, the revision rates reported varied significantly. This may be due to differences in the size of fusion constructs and baseline characteristics of the patient populations. Using the mean of multiple cost values and revision values helps limit these biases. Additionally, the technique used for CA will significantly affect final costs as the different instruments and hardware used vary significantly in cost. As there is no literature comparing the costs of the different techniques, this could not be taken into account in our value analysis. Finally, this cost analysis did not consider improvements in patient quality of life or compare TL fusion with CA to nonoperative management, which may increase the tolerable revision rate to make CA cost-effective. Future studies should focus on determining the value of CA using both revision data along with quality-adjusted life years (QALYs) based on patient-reported outcomes.

There are many questions which need to be addressed to fully determine the value of CA of pedicle screws. The technique resulting in the best biomechanics and clinical outcomes remains controversial.^{12,15,17,18} CA after PJK has also been shown to be beneficial and has the potential to be more cost-effective than prophylactic CA.⁵¹ Similarly, augmentation with calcium phosphate⁵²⁻⁵⁵ and calcium sulfate⁵⁶ have been used as alternatives to PMMA cement. Many have also discussed the risk of epidural leakage of cement and subsequent neurologic deficits^{11,17,25,26,28,29} and pulmonary embolism^{27,57} as complications of CA. All these factors change the cost and ultimately value of CA. For this reason, we recommend the surgeon to take cost into consideration along with the likely clinical benefits when deciding on which CA technique to use and levels to augment. Additionally, all surgeons should recommend starting osteoporosis treatment prior to an instrumented fusion in hopes to decrease ORC and revision operations in these patients whether CA is used or not.⁷

CA of pedicle screws for TL fusion surgery may be an effective strategy to decrease ORC and revision surgery. Cost analysis showed a decrease in revision surgery of 13.7% is required to make prophylactic CA a cost-effective strategy. This is close to the mean decrease in revision surgeries reported in comparative studies in the literature. Future studies should focus on the optimal CA technique to reduce cost and revision surgeries and use QALY data to help determine the true value of CA.



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References

- Coughlan T, Dockery F. Osteoporosis and fracture risk in older people. *Clin Med (Lond)*. 2014;14:187-191. doi:10.7861/clinmedicine.14-2-187
- Curtis EM, Woolford S, Holmes C, Cooper C, Harvey NC. General and specific considerations as to why osteoporosis-related care is often suboptimal. *Curr Osteoporos Rep*. 2020;18:38-46. doi:10.1007/s11914-020-00566-7
- Lehman RA Jr, Kang DG, Wagner SC. Management of osteoporosis in spine surgery. *J Am Acad Orthop Surg*. 2015;23:253-263. doi:10.5435/jaaos-d-14-00042
- Chin DK, Park JY, Yoon YS, et al. Prevalence of osteoporosis in patients requiring spine surgery: incidence and significance of osteoporosis in spine disease. *Osteoporos Int*. 2007;18:1219-1224. doi:10.1007/s00198-007-0370-8
- Bjerke BT, Zarrabian M, Aleem IS, et al. Incidence of osteoporosis-related complications following posterior lumbar fusion. *Global Spine J*. 2018;8:563-569. doi:10.1177/2192568217743727
- O'Leary PT, Bridwell KH, Lenke LG, et al. Risk factors and outcomes for catastrophic failures at the top of long pedicle screw constructs: a matched cohort analysis performed at a single center. *Spine (Phila Pa 1976)*. 2009;34:2134-2139. doi:10.1097/BRS.0b013e3181b2e17e
- Cerpa M, Sardar Z, Lenke L. Revision surgery in proximal junctional kyphosis. *Eur Spine J*. 2020;29(suppl 1):78-85. doi:10.1007/s00586-020-06320-y
- Santoni BG, Hynes RA, McGilvray KC, et al. Cortical bone trajectory for lumbar pedicle screws. *Spine J*. 2009;9:366-373. doi:10.1016/j.spinee.2008.07.008
- Wenger M, Markwalder TM. Vertebroplasty combined with pedicular instrumentation. *J Clin Neurosci*. 2008;15:257-262. doi:10.1016/j.jocn.2006.07.015
- Wenger M, Markwalder TM. Surgically controlled, transpedicular methyl methacrylate vertebroplasty with fluoroscopic guidance. *Acta Neurochir (Wien)*. 1999;141:625-631. doi:10.1007/s007010050352
- Chang MC, Liu CL, Chen TH. Polymethylmethacrylate augmentation of pedicle screw for osteoporotic spinal surgery: a novel technique. *Spine (Phila Pa 1976)*. 2008;33:E317-E324. doi:10.1097/BRS.0b013e31816f6c73
- Burval DJ, McLain RF, Milks R, Inceoglu S. Primary pedicle screw augmentation in osteoporotic lumbar vertebrae: biomechanical analysis of pedicle fixation strength. *Spine (Phila Pa 1976)*. 2007;32:1077-1083. doi:10.1097/01.brs.0000261566.38422.40
- Sawakami K, Yamazaki A, Ishikawa S, Ito T, Watanabe K, Endo N. Polymethylmethacrylate augmentation of pedicle screws increases the initial fixation in osteoporotic spine patients. *J Spinal Disord Tech*. 2012;25:E28-E35. doi:10.1097/BSD.0b013e318228bbcd
- Chen LH, Tai CL, Lai PL, et al. Pullout strength for cannulated pedicle screws with bone cement augmentation in severely osteoporotic bone: influences of radial hole and pilot hole tapping. *Clin Biomech (Bristol, Avon)*. 2009;24:613-618. doi:10.1016/j.clinbiomech.2009.05.002

15. Chen LH, Tai CL, Lee DM, et al. Pullout strength of pedicle screws with cement augmentation in severe osteoporosis: a comparative study between cannulated screws with cement injection and solid screws with cement pre-filling. *BMC Musculoskelet Disord.* 2011;12:33. doi:10.1186/1471-2474-12-33
16. Tolunay T, Arslan K, Yaman O, Dalbayrak S, Demir T. Biomechanical performance of various cement-augmented cannulated pedicle screw designs for osteoporotic bones. *Spine Deform.* 2015;3:205-210. doi:10.1016/j.jspd.2014.09.055
17. Becker S, Chavanne A, Spitaler R, et al. Assessment of different screw augmentation techniques and screw designs in osteoporotic spines. *Eur Spine J.* 2008;17:1462-1469. doi:10.1007/s00586-008-0769-8
18. Aycan MF, Yaman ME, Usta Y, Demir T, Tolunay T. Investigation of toggling effect on pullout performance of pedicle screws. *Proc Inst Mech Eng H: J Eng Med.* 2018;232:395-402. doi:10.1177/0954411918755417
19. Weiser L, Huber G, Sellenschloh K, et al. Insufficient stability of pedicle screws in osteoporotic vertebrae: biomechanical correlation of bone mineral density and pedicle screw fixation strength. *Eur Spine J.* 2017;26:2891-2897. doi:10.1007/s00586-017-5091-x
20. Coe JD, Warden KE, Herzig MA, McAfee PC. Influence of bone mineral density on the fixation of thoracolumbar implants. A comparative study of transpedicular screws, laminar hooks, and spinous process wires. *Spine (Phila Pa 1976).* 1990;15:902-907. doi:10.1097/00007632-199009000-00012
21. Rometsch E, Spruit M, Zigler JE, et al. Screw-related complications after instrumentation of the osteoporotic spine: a systematic literature review with meta-analysis. *Global Spine J.* 2020;10:69-88. doi:10.1177/2192568218818164
22. Liu D, Zhang B, Xie QY, et al. Biomechanical comparison of pedicle screw augmented with different volumes of polymethylmethacrylate in osteoporotic and severely osteoporotic cadaveric lumbar vertebrae: an experimental study. *Spine J.* 2016;16:1124-1132. doi:10.1016/j.spinee.2016.04.015
23. Choma TJ, Pfeiffer FM, Swope RW, Hirner JP. Pedicle screw design and cement augmentation in osteoporotic vertebrae: effects of fenestrations and cement viscosity on fixation and extraction. *Spine (Phila Pa 1976).* 2012;37:E1628-E1632. doi:10.1097/BRS.0b013e3182740e56
24. Kebaish KM, Martin CT, O'Brien JR, LaMotta IE, Voros GD, Belkoff SM. Use of vertebroplasty to prevent proximal junctional fractures in adult deformity surgery: a biomechanical cadaveric study. *Spine J.* 2013;13:1897-1903. doi:10.1016/j.spinee.2013.06.039
25. Abousayed M, Bektor JG, Sultan AM, Koptan W, El-Miligi Y. Augmentation of fenestrated pedicle screws with cement in patients with osteoporotic spine. *J Craniovertebr Junction Spine.* 2018;9:20-25. doi:10.4103/jcvjs.JCVJS_14_18
26. Martin CT, Skolasky RL, Mohamed AS, Kebaish KM. Preliminary results of the effect of prophylactic vertebroplasty on the incidence of proximal junctional complications after posterior spinal fusion to the low thoracic spine. *Spine Deform.* 2013;1:132-138. doi:10.1016/j.jspd.2013.01.005
27. Aydogan M, Ozturk C, Karatoprak O, Tezer M, Aksu N, Hamzaoglu A. The pedicle screw fixation with vertebroplasty augmentation in the surgical treatment of the severe osteoporotic spines. *J Spinal Disord Tech.* 2009;22:444-447. doi:10.1097/BSD.0b013e31818e0945
28. Raman T, Miller E, Martin CT, Kebaish KM. The effect of prophylactic vertebroplasty on the incidence of proximal junctional kyphosis and proximal junctional failure following posterior spinal fusion in adult spinal deformity: a 5-year follow-up study. *Spine J.* 2017;17:1489-1498. doi:10.1016/j.spinee.2017.05.017
29. Xie Y, Fu Q, Chen ZQ, et al. Comparison between two pedicle screw augmentation instrumentations in adult degenerative scoliosis with osteoporosis. *BMC Musculoskelet Disord.* 2011;12:286. doi:10.1186/1471-2474-12-286
30. Hart RA, Prendergast MA, Roberts WG, Nesbit GM, Barnwell SL. Proximal junctional acute collapse cranial to multi-level lumbar fusion: a cost analysis of prophylactic vertebral augmentation. *Spine J.* 2008;8:875-881. doi:10.1016/j.spinee.2008.01.015
31. Ghobrial GM, Eichberg DG, Kolcun JPG, et al. Prophylactic vertebral cement augmentation at the uppermost instrumented vertebra and rostral adjacent vertebra for the prevention of proximal junctional kyphosis and failure following long-segment fusion for adult spinal deformity. *Spine J.* 2017;17:1499-1505. doi:10.1016/j.spinee.2017.05.015
32. Theologis AA, Burch S. Prevention of acute proximal junctional fractures after long thoracolumbar posterior fusions for adult spinal deformity using 2-level cement augmentation at the upper instrumented vertebra and the vertebra 1 level proximal to the upper instrumented vertebra. *Spine (Phila Pa 1976).* 2015;40:1516-1526. doi:10.1097/brs.0000000000001043
33. Goost H, Kabir K, Wirtz DC, et al. PMMA augmentation of pedicle screws: results of a survey in Germany [in German]. *Z Orthop Unfall.* 2012;150:318-323. doi:10.1055/s-0031-1298371
34. Theologis AA, Miller L, Callahan M, et al. Economic impact of revision surgery for proximal junctional failure after adult spinal deformity surgery: a cost analysis of 57 operations in a 10-year experience at a major deformity center. *Spine (Phila Pa 1976).* 2016;41:E964-E972. doi:10.1097/BRS.0000000000001523
35. Jain A, Yeramaneni S, Kebaish KM, et al. Cost-utility analysis of rhBMP-2 use in adult spinal deformity surgery. *Spine (Phila Pa 1976).* 2020;45:1009-1015. doi:10.1097/brs.0000000000003442
36. Varshneya K, Azad TD, Pendharkar AV, et al. Adult spinal deformity surgery in patients with movement disorders: a propensity-matched analysis of outcomes and cost. *Spine (Phila Pa 1976).* 2020;45:E288-E295. doi:10.1097/brs.0000000000003251
37. Neal CJ, Mandell K, Tasikas E, et al. Cost-effectiveness of adult spinal deformity surgery in a military healthcare system. *Neurosurg Focus.* 2018;45:E11. doi:10.3171/2018.9.Focus18381
38. McCarthy IM, Hostin RA, O'Brien MF, et al. Analysis of the direct cost of surgery for four diagnostic categories of adult spinal deformity. *Spine J.* 2013;13:1843-1848. doi:10.1016/j.spinee.2013.06.048
39. Raman T, Nayar SK, Liu S, Skolasky RL, Kebaish KM. Cost-effectiveness of primary and revision surgery for adult spinal deformity. *Spine (Phila Pa 1976).* 2018;43:791-797. doi:10.1097/brs.0000000000002481

40. Yeramane S, Gum JL, Carreon LY, et al. Impact of readmissions in episodic care of adult spinal deformity: event-based cost analysis of 695 consecutive cases. *J Bone Joint Surg Am.* 2018; 100:487-495. doi:10.2106/jbjs.16.01589
41. Terran J, McHugh BJ, Fischer CR, et al. Surgical treatment for adult spinal deformity: projected cost effectiveness at 5-year follow-up. *Ochsner J.* 2014;14:14-22.
42. Kelly MP, Lenke LG, Bridwell KH, Agarwal R, Godzik J, Koster L. Fate of the adult revision spinal deformity patient: a single institution experience. *Spine (Phila Pa 1976).* 2013;38:E1196-E1200. doi:10.1097/BRS.0b013e31829e764b
43. Pichelmann MA, Lenke LG, Bridwell KH, Good CR, O'Leary PT, Sides BA. Revision rates following primary adult spinal deformity surgery: six hundred forty-three consecutive patients followed-up to twenty-two years postoperative. *Spine (Phila Pa 1976).* 2010;35:219-226. doi:10.1097/BRS.0b013e3181c91180
44. Martin BI, Mirza SK, Comstock BA, Gray DT, Kreuter W, Deyo RA. Reoperation rates following lumbar spine surgery and the influence of spinal fusion procedures. *Spine (Phila Pa 1976).* 2007;32:382-387. doi:10.1097/01.brs.0000254104.55716.46
45. Chen S, Luo M, Wang Y, Liu H. Stopping at sacrum versus nonsacral vertebra in long fusion surgery for adult spinal deformity: meta-analysis of revision with minimum 2-year follow-up. *World Neurosurg.* Published online December 31, 2018. doi:10.1016/j.wneu.2018.12.102
46. Tosteson AN, Tosteson TD, Lurie JD, et al. Comparative effectiveness evidence from the spine patient outcomes research trial: surgical versus nonoperative care for spinal stenosis, degenerative spondylolisthesis, and intervertebral disc herniation. *Spine (Phila Pa 1976).* 2011;36:2061-2068. doi:10.1097/BRS.0b013e318235457b
47. Paulus MC, Kalantar SB, Radcliff K. Cost and value of spinal deformity surgery. *Spine (Phila Pa 1976).* 2014;39:388-393. doi:10.1097/brs.0000000000000150
48. McCarthy I, O'Brien M, Ames C, et al. Incremental cost-effectiveness of adult spinal deformity surgery: observed quality-adjusted life years with surgery compared with predicted quality-adjusted life years without surgery. *Neurosurg Focus.* 2014;36:E3. doi:10.3171/2014.3.Focus1415
49. Scheer JK, Hostin R, Robinson C, et al. Operative management of adult spinal deformity results in significant increases in QALYs gained compared to nonoperative management: analysis of 479 patients with minimum 2-year follow-up. *Spine (Phila Pa 1976).* 2018;43:339-347. doi:10.1097/brs.0000000000001626
50. Alvin MD, Miller JA, Lubelski D, et al. Variations in cost calculations in spine surgery cost-effectiveness research. *Neurosurg Focus.* 2014;36:E1. doi:10.3171/2014.3.Focus1447
51. Jesse MK, Cleveland AW 3rd, Reiter MJ, Patel VV, Kleck CJ. Transpedicular-transdiscal cement augmentation treatment of thoracolumbar fusion proximal junctional failure. *Int J Spine Surg.* 2019;13:470-473. doi:10.14444/6062
52. Criado A, Yokhana S, Rahman T, McCarty S, Andrecovich C, Ren W, Yassir WK. Biomechanical strength comparison of pedicle screw augmentation using poly-dicalcium phosphate dihydrate (P-DCPD) and polymethylmethacrylate (PMMA) cements. *Spine Deform.* 2020;8:165-170. doi:10.1007/s43390-019-00022-2
53. Masaki T, Sasao Y, Miura T, et al. An experimental study on initial fixation strength in transpedicular screwing augmented with calcium phosphate cement. *Spine (Phila Pa 1976).* 2009; 34:E724-E728. doi:10.1097/BRS.0b013e3181adc0e9
54. Leung KS, Siu WS, Li SF, et al. An in vitro optimized injectable calcium phosphate cement for augmenting screw fixation in osteopenic goats. *J Biomed Mater Res B Appl Biomater.* 2006; 78:153-160. doi:10.1002/jbm.b.30467
55. Hashemi A, Bednar D, Ziada S. Pullout strength of pedicle screws augmented with particulate calcium phosphate: an experimental study. *Spine J.* 2009;9:404-410. doi:10.1016/j.spinee.2008.07.001
56. Yi X, Wang Y, Lu H, Li C, Zhu T. Augmentation of pedicle screw fixation strength using an injectable calcium sulfate cement: an in vivo study. *Spine (Phila Pa 1976).* 2008;33:2503-2509. doi:10.1097/BRS.0b013e318184e750
57. Choe DH, Marom EM, Ahrar K, Truong MT, Madewell JE. Pulmonary embolism of polymethyl methacrylate during percutaneous vertebroplasty and kyphoplasty. *AJR Am J Roentgenol.* 2004;183:1097-1102. doi:10.2214/ajr.183.4.1831097