The Cortical Bone Trajectory for Pedicle Screw Insertion

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Abstract

» The cortical bone trajectory takes advantage of a cortically based track through the pedicle, which may result in improved fixation strength compared with a traditionally placed pedicle screw.

» The cortical track is a medially to laterally, caudally to cranially directed path that allows for less soft-tissue dissection during insertion, making it amenable to minimally invasive techniques and useful in cases of trauma and adjacent segment disease.

» Complications with this new technology have been low, and outcome studies have demonstrated excellent fusion rates as well as maintenance of reduction in cases of spondylolisthesis.

» Early promising results should be tempered with reports of failure during early implementation; a learning curve exists and ultimately, larger, prospective, high-quality studies are necessary before the advantages of cortical screw instrumentation can truly be quantified.

Pedicle screw fixation for spinal stabilization is now commonplace in spine surgery. Traditionally, pedicle screws are placed through a trajectory in which screw insertion utilizes a transpedicular path through the axis of the pedicle, either paralleling the end plate, as in the straightforward trajectory, or following the anatomic axis of the pedicle with an approximately 22° cephalocaudal trajectory through the pedicle, as in the anatomic trajectory[1].

In 2009, Santoni et al. introduced a novel pedicle screw trajectory and called the path the cortical bone track[2].

Traditional pedicle screws obtain 60% to 80% of their stability within the denser cortical bone of the pedicle, with the remainder of fixation obtained through the weaker cancellous bone located in the vertebral body[3]. In osteoporosis, as primarily trabecular bone is compromised, the fixation strength of these screws diminishes and increased rates of loosening are seen[3-6].

Compared with traditional pedicle screws, the cortical bone track screws (from here on referred to as cortical screws) take advantage of a cortically based track through the pedicle and were developed precisely to address loosening rates seen in osteoporotic bone. This new track follows a laterally directed trajectory in the transverse plane and a superiorly directed track in the sagittal plane (Figs. 1-A and 1-B). The hope was that this modified technique would provide enhanced screw purchase and interface strength independent of trabecular bone mineral density, which may be advantageous in the setting of compromised bone.

The Cortical Bone Track and Technique

Although initially introduced by Santoni et al., Matsukawa et al.[7] later performed a morphometric analysis of the cortical bone

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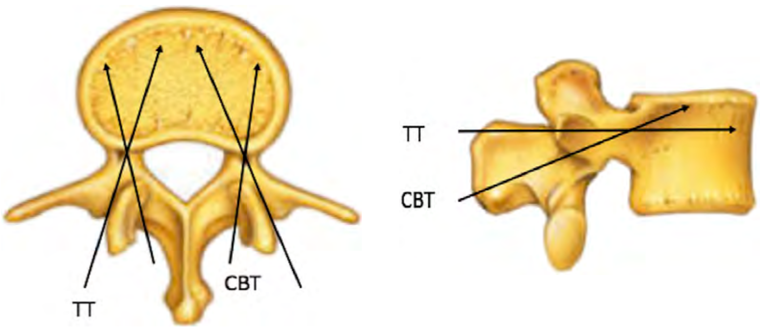

Figs. 1-A and 1-B Illustrations of a lumbar vertebra. **Fig. 1-A** Axial view demonstrating the laterally to medially directed traditional trajectory (TT) compared with the medially to laterally directed cortical bone track (CBT). **Fig. 1-B** Sagittal projection showing the straight-forward screw path of TT compared with the caudal to cranial trajectory of the CBT screw.

track to better detail its dimensions and trajectory. For the measurements of the track, a starting point was defined at the junction of the center of the superior articular facet and a line 1 mm inferior to the inferior border of the transverse process of the lumbar vertebra. Radiographically, the starting point was determined to lie in the 5 o'clock position of the left pedicle and in the 7 o'clock position of the right pedicle when viewed from the traditional posterior approach (Fig. 2). The measurements of the track were made from the starting point at the dorsal cortex to the most anterior part of the track, which was formed by a line from the starting point to the midpoint of the pedicle in the mediolateral plane (axial) and the cephalocaudal plane (sagittal) and was extended as ventrally as possible to the vertebral body. This yielded an approximate transverse angle of insertion of 10° and a mean sagittal angle of insertion of 25°. The distance from the screw to the lateral edge of the pars depended on the vertebra, increasing in a caudal direction. For the cephalad vertebral levels, the starting point is about 1 mm from the edge of the pars, which predisposes to a potential pars fracture. However, studies have found that the upper lumbar vertebral levels have a thicker pars than the caudal levels and the bone at the pars is thicker laterally than medially, both mitigating fracture risk[8].

A later study by Matsukawa et al.[9] attempted to formulate the ideal trajectory for cortical screws and found that insertional torque, a measure of pullout strength[10], increased with the increasing length of the screw within the dorsal lamina, with fixation in the inferior half of the pedicle, and with engagement of the posterior third to half of the vertebral body. Similarly, the superior vertebral end plate and lateral vertebral walls, both of which are ideally engaged with this screw track, have been shown to have increased bone density compared with other vertebral elements[11,12]. This led to

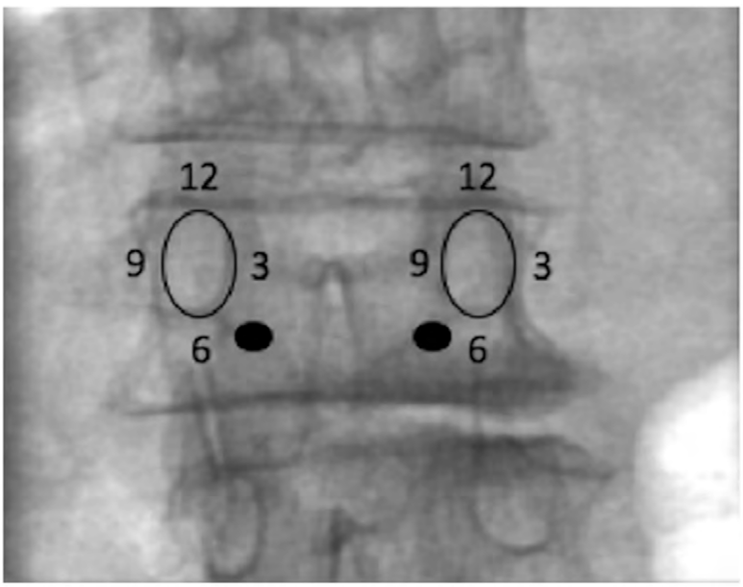

Fig. 2

Posteroanterior radiograph of an L3 vertebra depicting the described clock face of the pedicle. The cortical bone track screw starting point is at 7 o'clock (black dot on the right pedicle) for the right pedicle and 5 o'clock (black dot on the left pedicle) for the left pedicle.

TABLE I Distance from Starting Point to the Lateral Edge of the Pars*

Vertebral Level	Distance to Starting Point† *(mm)*
L1	0.8 ± 1.1
L2	1.5 ± 1.2
L3	2.0 ± 1.1
L4	3.3 ± 1.1
L5	4.7 ± 1.0

*Data in this table were obtained from: Matsukawa K, Yato Y, Nemoto O, Imabayashi H, Asazuma T, Nemoto K. Morphometric measurement of cortical bone trajectory for lumbar pedicle screw insertion using CT. J Spinal Disord Tech. 2013 Aug;26(6): E248-53. †The values are given as the mean and the standard deviation.

the modification of the track to incorporate these elements into the cortical screw trajectory.

The technique is as follows. The use of fluoroscopy or navigation is recommended, but not required, for screw placement, as the only study with screw malposition occurred in the original description by Santoni et al., which did not use image guidance.

The starting point should be at the 5 or 7 o'clock position depending on the left or right-sided pedicle. The anatomic starting point is approximately 1 mm inferior to the inferior border of the transverse process and at the center of the superior articular process. The mediolateral starting point is 1 mm from the edge of the pars for L1 and located sequentially farther from the pars edge at more caudal vertebral levels (Table I). Regardless of these relative landmarks, anteroposterior fluoroscopy may be used to confirm that each starting point is along the silhouette of the pedicle at either the 5 o'clock position or the 7 o'clock position and a burr may be used to create an appropriate starting point.

As this is a cortically based track, a drill is used to drill the entire track. Because the pars is composed of dense cortical bone, the drill-bits are usually specific to the minor diameter of the intended screw size. An appropriately sized drill-bit is used to create a starting point in the dorsal cortex and along the cortical screw trajectory aiming at the 11 o'clock direction (if it is the left pedicle) or the 1 o'clock direction (if it is the right pedicle) on the pedicle clock face. The approximate angle is 10° medial to lateral and 25° caudal to cranial. On a lateral fluoroscopic image, the trajectory should be aimed to engage the inferior half of the pedicle and end at the posterior third to half of the vertebral body (Fig. 3-A). We prefer to drill initially to a depth of 25 mm to verify the preservation of the pedicle walls and subsequently to the depth of the intended screw (generally 35 to 40 mm).

A ball-tipped probe can then be used to check that the pedicle has not been violated. Violation of the lateral vertebral body rarely causes neurovascular injury and a screw can still be inserted. Violation of the inferior or medial wall of the pedicle requires repositioning of the pilot hole or conversion to a traditional pedicle screw trajectory.

After drilling, line-to-line tapping is performed so that if a 5.5-mm screw is to be inserted, a 5.5-mm tap should be used (Fig. 3-B). The ideal screw length is usually 35 to 40 mm, engaging the vertebral body (Fig. 3-C)[13].

Biomechanics

Trying to quantify the theoretically increased fixation afforded by cortical screws, Matsukawa et al.[14] measured the intraoperative insertional torque of 162 cortical screws and compared it with that of 36 traditional screws. Insertional torque is the shearing and frictional forces created by the bone-screw interface and is ultimately the force that allows the screw to advance in bone. In 1993, Zdeblick et al.[10] showed that insertional torque correlated with pullout

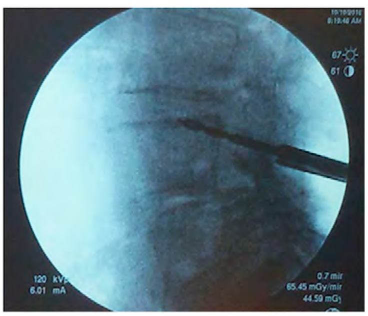

Fig. 3-A

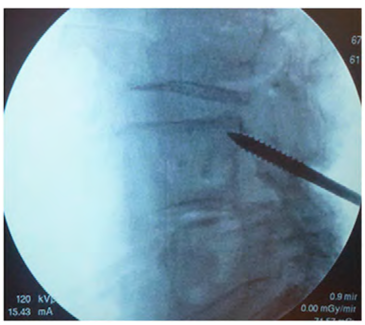

Fig. 3-B

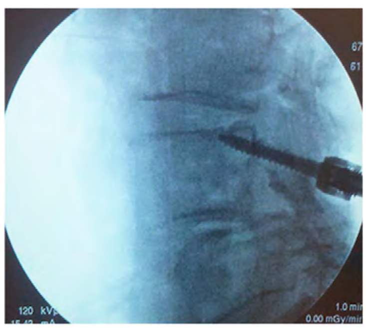

Fig. 3-C

Figs. 3-A, 3-B, and 3-C Fluoroscopic images showing the localized cortical bone trajectory. **Fig. 3-A** A drill is used to create the path of the cortical bone track pedicle screw starting at the inferior half of the pedicle and aiming for the posterior half of the vertebral body at approximately a 25° caudal to cranial angle on the lateral fluoroscopic view. **Fig. 3-B** For a 5.5-mm-diameter screw, a 5.5-mm tap is used (line to line). **Fig. 3-C** A 5.5 × 35-mm cortical screw is placed in the final position.

strength and was a measure of ultimate screw fixation. Matsukawa et al.[14] found that in the vertebrae that had a cortical screw in one pedicle and a traditional screw in the other pedicle, the insertional torque of the cortical screw was 71% greater than that of the traditional screws ($p < 0.01$). Insertional torque was even greater when entire cortical screw constructs were compared with traditional screw constructs, with a 101% increased insertional torque for the cortical screws ($p < 0.01$).

A later study by the same group analyzed several factors to determine their effects on insertional torque for cortical screws[9]. The results showed that femoral bone mineral density ($p < 0.01$), screw length within the lamina ($p = 0.03$), and the cephalad screw angle ($p = 0.04$) were significant independent factors affecting insertional torque, with femoral bone mineral density as measured by dual x-ray absorptiometry being the strongest factor affecting the insertional torque. Conversely, Santoni et al. concluded that cortical screw fixation was independent of bone mineral density, which was a proposed benefit in the setting of osteoporosis[2]. The effect of bone mineral density on cortical screw fixation is unclear, given these conflicting results.

Interestingly, rather than total screw length, screw length within the dorsal cortex, referred to by Matsukawa et al. as the dorsal lamina, was paramount. The laminar portion of the cortical screw, where cortical bone is concentrated specifically between the pars interarticularis region and the inferior part of the pedicle, enhances pullout strength[8]. Similarly, increasing the caudal to cranial angle allows for greater fixation into this denser region and is likely the reason for increased insertional torque identified with this factor.

This theoretically increased pullout strength as gauged by insertional torque has been corroborated in the seminal work by Santoni et al.[2] Although not reaching significance, cortical screws were found to have a 30% increased pullout strength when compared with traditional pedicle screws ($p = 0.080$). When the cortical screw construct was compared with the traditional pedicle screw construct with craniocaudal toggling, no differences between the two were identified ($p = 0.354$).

Toggle strength, assessed with shear, tension, and bending stresses, may be more reflective of in vivo functioning. Baluch et al.[15] compared the toggle strength of cortical and traditional pedicle screws fixed in normal bone by cyclic loading until 2-mm head displacement was noted and found that cortical screws had superior resistance to craniocaudal cyclic loading ($p = 0.002$).

Conversely, Akpolat et al.[16] compared resistance with sagittal bending of cortical and traditional pedicle screws fixed in compromised bone, which were stressed for 100 cycles or until 6° of loosening was observed. Traditional pedicle screws showed improved fixation strength under these conditions ($p < 0.001$), with cortical screws never being able to withstand a full 100 cycles.

As cortical screws gain popularity, they are being used increasingly with interbody devices (Figs. 4-A and 4-B). Perez-Orribo et al.[17] compared cortical screw strength with traditional pedicle screw strength in the setting of an intact disc and with transforaminal interbody

Fig. 4-A

Fig. 4-B

Figs. 4-A and 4-B Radiographs showing the 1-year follow-up posteroanterior view (**Fig. 4-A**) and lateral view (**Fig. 4-B**) of L4-L5 degenerative spondylolisthesis managed with transformational interbody fusion and cortical bone track pedicle screw fixation.

fixation and direct lateral interbody fixation. With an intact disc, there was no difference in construct stability except for that during axial rotation, for which traditional pedicle screw fixation was superior ($p = 0.010$). When compared in the setting of direct lateral interbody fixation, there was no difference in any testing modality. In the setting of transforaminal interbody fixation, the cortical screw-rod construct was significantly less stiff during lateral bending than the traditional pedicle screw-rod construct ($p = 0.022$). Some authors have suggested using interbody cages when choosing cortical screw fixation on the basis of these findings and their own clinical experience[18,19].

Indications

Osteoporosis

Although there are no true indications for cortical screw fixation, rather than pedicle screw fixation, several relative indications, or ideal circumstances for use, have emerged. The cortical bone track was initially developed to obtain enhanced fixation in the setting of osteoporosis, and this was the original indication for its use[2].

Minimally Invasive Surgery

More recently, cortical screws have been increasingly used in the setting of minimally invasive surgery as the dissection required for insertion of the medially to laterally directed screws requires a narrower field than for pedicle screws placed using the traditional trajectory (laterally to medially directed) by means of an open technique.

It is precisely this narrower dissection and inferior starting point relative to traditional pedicle screws that have expanded its indications elsewhere. Matsukawa et al.[20] reviewed their 4-year data on cortical screws to assess the prevalence of facet joint violation. The rate of facet joint violation was 11.8%, with no cases of frank intra-articular insertion. This is a marked improvement from published rates of facet joint violation, ranging from 25% to 100%, using traditional pedicle screws[21]. Facet joint violation may lead to increased facet loading and mechanical instability at adjacent segments, and some have suggested that facet joint violation is closely related to radiographic and symptomatic adjacent segment disease[22,23]. In turn, rates of adjacent segment disease following cortical screw placement are lower (3.2%) than when traditional pedicle screws are used (11%)[19].

Trauma

Mobbs[24] described taking advantage of the minimal dissection and sparing of the facet joint during trauma cases. In this setting, the superior articular facets may already be compromised and further violation through dissection or placement of screws through the facet joint may lead to further destabilization. He described a technique of placing traditional pedicle screws at the inferior level and sparing the superior level by placing cortical screws above.

Adjacent Segment Disease

Cortical screws have also been used successfully to manage adjacent segment disease[25]. Rather than exposing the entirety of the prior screw-rod construct, some have advocated exposing only the degenerated and adjacent levels. Cortical screws are placed at the new level as well as in conjunction with previously placed pedicle screws at the adjacent level (e.g., for L2 degeneration above prior fixation in L3, place cortical screws in L2 and cortical screws along with the screws previously placed at the pedicle of L3). The new cortical screws are then linked to a new rod allowing fusion of the adjacent level, sparing the added morbidity of a revision exposure. The ability to perform this technique hinges on the potential for the pedicle to accommodate 2 screws. A preoperative computed tomographic (CT) scan is very helpful in this regard, as the amount of residual, uninstrumented pedicle can be determined with accuracy. A cortical track of at least 5 mm is recommended as the smallest cortical threaded pedicle screw is 4.5 mm.

Other options for fixation in the setting of adjacent segment disease include placing cortical screws at the degenerated level and then attaching a rod to those screws and linking that construct to the existing pedicle screw construct with connectors. Alternatively, some have cut and removed the existing rod and pedicle screw at the adjacent level and replaced those screws with cortical screws. Cortical screws are placed at the degenerated level as well and the 2 levels are then linked with a new rod.

Rescue Screws

Cortical screws have also been used as rescue screws in cases of a failed or compromised pedicle screw construct in the lumbar spine. Calvert et al.[26] used a cadaver model to test the stiffness of a traditional pedicle screw and cortical screw constructs. After the screws were loaded to failure and were removed, the other screw type (cortical for failed traditional and traditional for failed cortical) was inserted in the same pedicle. The rescue pedicle screws provided stiffness similar to that provided by the primary screw construct in flexion and extension, lateral bending, and axial rotation. In subsequent pullout testing of those screws, cortical rescue screws retained 60% of the original pedicle screw pullout strength and traditional pedicle rescue screws retained 65% of the original cortical screw pullout strength. The authors concluded that cortical and pedicle screws each retain adequate construct stiffness and pullout strength when used for revision at the same level.

Complications

The starting point and trajectory of the cortical screw predispose the vertebrae to predictable potential complications. Pars and pedicle fractures may occur. Fortuitously, pars thickness increases moving from medial to lateral on the pars itself so that a lateral starting point is not as risky as it may seem. Moreover, although the pars itself narrows at more cephalad levels, the bone density (thickness) of the pars increases at those levels as well. A pars fracture requires conversion to a traditional pedicle screw trajectory as the starting point and a critical structure for fixation is compromised.

The rates of screw malposition have been reported to be exceedingly low. However, most studies used intraoperative fluoroscopy or navigation and those studies found a 0% medial breach rate[18,27,28]. Santoni et al.[2] did not use any image guidance in their series and identified a 20% prevalence of medial breach with this technique. In their retrospective review, Sakaura et al.[19] compared cortical screws with traditional screws, both augmented with posterior lumbar interbody fusion, and identified a 2.1% screw malposition rate for the cortical bone trajectory compared with a 3.7% malposition rate for the traditional screws[19].

Snyder et al.[27] reported their complication rate for 79 patients who underwent cortical bone screw fixation for degenerative disease. Image guidance was used for 87% of cases, with 81% of cases fused with an interbody device. The rate of complication was 8.9% (9 complications in 7 of 79 patients). These included implant failure (n = 2), pseudarthrosis (n = 2), thrombosis (pulmonary embolism or deep vein thrombosis) (n = 3), epidural hematoma (n = 1), and deep wound infection requiring surgical debridement (n = 1). There were no dural tears, no nerve-root injuries, and no misplaced screws as determined on immediate postoperative imaging.

Outcomes

The majority of studies documenting clinical use of cortical screws are short-term, consisting mostly of retrospective case controls or case series, and recommendations for use are largely expert opinion.

The only prospective study evaluating cortical screws, to our knowledge, is a noninferiority trial that was not designed to demonstrate the superiority of cortical screws to pedicle screws, but rather to determine whether the outcomes of cortical screw fixation are significantly worse. Lee et al.[28] randomized 79 patients to posterior lumbar interbody fusion with cortical screws or traditional pedicle screws for cases of single-level degenerative lumbar spondylolisthesis with the primary outcome of fusion rates. At 1 year, there was no significant difference ($p = 0.61$) in fusion rates between the 2 groups (87.2% for cortical screws compared with 92.1% for pedicle screws). Cortical screw utilization provided improved function at 1 week ($p = 0.02$), but the difference in Oswestry Disability Index scores was not significant at any other time point. Consistent with minimally invasive surgery literature, operative time ($p = 0.03$), blood loss ($p = 0.04$), and incision length ($p = 0.03$) were all significantly diminished in the cortical screw cohort.

Sakaura et al.[19] performed the largest retrospective study of cortical screw fixation, comparing mean 3-year follow-up data of 95 patients who underwent posterior lumbar interbody fusion with cortical screw fixation with the data of 82 historical controls who underwent posterior lumbar interbody fusion with traditional pedicle screw fixation for degenerative spondylolisthesis. In the cortical screw group, at the time of the latest follow-up, the overall fusion rate was 88.4%, with nonunion in 11 of 95 cases. Conversely, the overall fusion rate for the traditional pedicle screw group was 96.3%, with nonunion in only 3 of 82 cases. This difference trended toward significance, but fell short ($p = 0.052$). Sakaura et al.[19] attributed the increased nonunion rate to a potentially weaker construct with cortical screws, citing the aforementioned study by Perez-Orribo et al.[17], which found that even with transforaminal interbody fixation, cortical screw fixation was less stiff than traditional pedicle screw fixation in lateral bending. On the basis of these findings, Sakaura et al. recommended using a connector to stiffen the cortical screw-posterior lumbar interbody fusion construct. In their study, Lee et al. found that operative time was shorter with cortical screw fixation ($p < 0.01$), but no difference was identified in blood loss ($p > 0.05$) or improvement in the Japanese Orthopaedic Association (JOA) score[28].

Recently, 2 short-term studies evaluated the ability of cortical screws to maintain reduction in cases of degenerative spondylolisthesis[29,30]. Both studies found no significant difference in the percentage of slip reduction between a cohort of patients treated with cortical screw fixation and a cohort of patients treated with traditional pedicle screw fixation and no significant loss of reduction was identified in the cortical screw cohort at the time of the final follow-up. One of the 2 studies identified a 9% rate of loss of correction, with all of these cases occurring during the first 10 cases performed[30]. Mori et al. attributed this complication rate to technique error during posterior lumbar interbody fusion preparation and noted that, after more careful attention to end plate preparation and placement of 2 cages rather than 1 cage, there were no further instances of loss of correction. That series highlighted the potential learning curve for this novel technique.

Similarly, Glennie et al.[18] presented a more cautionary tale of cortical screw use. Their reported experience with cortical screw fixation was a case series of 8 patients with a minimum follow-up of 1 year. Most cases were single-level fusions for degenerative spondylolisthesis. Although 5 of 8 patients were satisfied at the time of the final follow-up, 5 of 8 cases had evidence of screw loosening and 50% of the patients had loss of reduction. In their series, the first 3 cases were performed without an interbody device, and, in each case, there was loss of reduction, accounting for 3 of the 4 instances of loss of reduction. Two of 8 patients, both with screw loosening, ultimately required revision at 1 year, 1 for pseudarthrosis and 1 for adjacent segment disease. The authors noted that their high rate of complication could be the result of an early learning curve, but advised caution when beginning to implement this new instrumentation. Based on their early failure without interbody devices, they recommended interbody device use for all cases employing cortical screws, as Sakaura et al. had similarly proposed.

Emerging Techniques

Until recently, cortical screw use had been limited to the lumbar spine. Matsukawa et al. have proposed a cortical screw track in both the sacrum and the lower thoracic spine[31,32]. Sacral fixation has proven challenging as the sacral pedicles are capacious and are composed mostly of cancellous bone. Moreover, regarding cortical screw fixation, given the medial starting point of lumbar cortical screws, a traditional lateral starting point for sacral screws makes rod connecting difficult.

Matsukawa et al.[31] developed a novel sacral screw trajectory precisely to address these shortcomings. The penetrating S1 end plate screw (PES)[31] maximizes engagement with denser bone by penetrating the S1 superior end plate and the lateral column of the S1 vertebral body through a more medial entry point than with a traditional trajectory. The PES technique demonstrated a 141% higher mean insertional torque than a traditional S1 pedicle screw ($p < 0.01$), and in their clinical experience, they have had no cases of loosening or breakage in 33 cases.

For the PES technique, the starting point is the junction of the center of the superior articular process of S1 and a line approximately 3 mm inferior to the inferior articular process of L5. The trajectory is directed straight ahead in the axial plane with 0° of screw convergence and is angulated cranially in the sagittal plane, penetrating the middle of the sacral end plate (approximately 30°). Because the cortical purchase at the starting point is considerably shorter for S1 cortical screws, Matsukawa et al.[31] recommend undersizing the tap by 1 mm, as is typically done with traditional pedicle screws.

In 2016, to address the challenges of fixation in osteoporotic bone, Matsukawa et al.[32] introduced a thoracic cortical bone track for use from T9 to T12, with more cephalad levels being too unsafe for adequately sized cortical screw placement given the pedicle dimensions. The described starting point begins at the intersection of the inferior border of the transverse process and the lateral two-thirds of the superior articular facet and has a straight-ahead trajectory in the transverse plane without convergence, angulated cranially in the sagittal plane toward the posterior third of the superior end plate. This track showed a 53.8% higher insertional torque compared with the straight-forward traditional pedicle screw trajectory ($p = 0.0003$).

Conclusions

The cortical screw is an appealing technology to deal with the problem of fixation in compromised bone. The exposure and anatomy for screw placement are familiar to surgeons and the cortical screw track provides a safe corridor traveling away from the neural elements. Cortical screws can be advantageous in the setting of osteoporotic bone, minimally invasive surgery, trauma, and adjacent segment disease. They can also avoid facet joint violation, potentially leading to lower rates of adjacent segment disease. Biomechanical studies have confirmed some of these potential advantages. However, others have suggested potential weaknesses that may require concomitant use of interbody devices.

On the basis of short-term, mostly retrospective studies, it seems that cortical screw fixation achieves largely equivalent results in terms of radiographic loss of correction and outcomes, with no significant differences in fusion or complication rates. However, early data must be tempered with reports such as those by Glennie et al., who presented substantial complication rates with early use. From both biomechanical and clinical series, interbody device use should strongly be considered.

Ultimately, larger, prospective, high-quality studies conducted across multiple centers are likely necessary before the advantages of cortical screw instrumentation can truly be quantified.

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References

1. Lehman RA Jr, Polly DW Jr, Kuklo TR, Cunningham B, Kirk KL, Belmont PJ Jr. Straight-forward versus anatomic trajectory technique of thoracic pedicle screw fixation: a biomechanical analysis. Spine (Phila Pa 1976). 2003 Sep 15;28(18):2058-65.

2. Santoni BG, Hynes RA, McGilvray KC, Rodriguez-Canessa G, Lyons AS, Henson MA, Womack WJ, Puttlitz CM. Cortical bone trajectory for lumbar pedicle screws. Spine J. 2009 May;9(5):366-73. Epub 2008 Sep 14.

3. Hirano T, Hasegawa K, Takahashi HE, Uchiyama S, Hara T, Washio T, Sugiura T, Yokaichiya M, Ikeda M. Structural characteristics of the pedicle and its role in screw stability. Spine (Phila Pa 1976). 1997 Nov 1;22(21):2504-9, discussion: 2510.

4. Esses SI, Sachs BL, Dreyzin V. Complications associated with the technique of pedicle screw fixation. A selected survey of ABS members. Spine (Phila Pa 1976). 1993 Nov;18(15):2231-8; discussion 2238-9.

5. Davne SH, Myers DL. Complications of lumbar spinal fusion with transpedicular instrumentation. Spine (Phila Pa 1976). 1992 Jun;17(6)(Suppl):S184-9.

6. Okuyama K, Sato K, Abe E, Inaba H, Shimada Y, Murai H. Stability of transpedicle screwing for the osteoporotic spine. An in vitro study of the mechanical stability. Spine (Phila Pa 1976). 1993 Nov;18(15):2240-5.

7. Matsukawa K, Yato Y, Nemoto O, Imabayashi H, Asazuma T, Nemoto K. Morphometric measurement of cortical bone trajectory for lumbar pedicle screw insertion using computed tomography. J Spinal Disord Tech. 2013 Aug;26(6):E248-53.

8. Weiner BK, Walker M, Wiley W, McCulloch JA. The lateral buttress: an anatomic feature of the lumbar pars interarticularis. Spine (Phila Pa 1976). 2002 Sep 1;27(17):E385-7.

9. Matsukawa K, Taguchi E, Yato Y, Imabayashi H, Hosogane N, Asazuma T, Nemoto K. Evaluation of the fixation strength of pedicle screws using cortical bone trajectory: what is the ideal trajectory for optimal fixation? Spine (Phila Pa 1976). 2015 Aug 1;40(15):E873-8.

10. Zdeblick TA, Kunz DN, Cooke ME, McCabe R. Pedicle screw pullout strength. Correlation with insertional torque. Spine (Phila Pa 1976). 1993 Sep 15;18(12):1673-6.

11. Wu SS, Edwards WT, Yuan HA. Stiffness between different directions of transpedicular screws and vertebra. Clin Biomech (Bristol, Avon). 1998;13(1)(Suppl 1):S1-8.

12. Grant JP, Oxland TR, Dvorak MF. Mapping the structural properties of the lumbosacral vertebral endplates. Spine (Phila Pa 1976). 2001 Apr 15;26(8):889-96.

13. Matsukawa K, Yato Y, Imabayashi H, Hosogane N, Abe Y, Asazuma T, Chiba K. Biomechanical evaluation of fixation strength among different sizes of pedicle screws using the cortical bone trajectory: what is the ideal screw size for optimal fixation? Acta Neurochir (Wien). 2016 Mar;158(3):465-71. Epub 2016 Jan 15.

14. Matsukawa K, Yato Y, Kato T, Imabayashi H, Asazuma T, Nemoto K. In vivo analysis of insertional torque during pedicle screwing using cortical bone trajectory technique. Spine (Phila Pa 1976). 2014 Feb 15;39(4):E240-5.

15. Baluch DA, Patel AA, Lullo B, Havey RM, Voronov LI, Nguyen NL, Carandang G, Ghanayem AJ, Patwardhan AG. Effect of physiological loads on cortical and traditional pedicle screw fixation. Spine (Phila Pa 1976). 2014 Oct 15;39(22):E1297-302.

16. Akpolat YT, İnceoğlu S, Kinne N, Hunt D, Cheng WK. Fatigue performance of cortical bone trajectory screw compared with standard trajectory pedicle screw. Spine (Phila Pa 1976). 2016 Mar;41(6):E335-41.

17. Perez-Orribo L, Kalb S, Reyes PM, Chang SW, Crawford NR. Biomechanics of lumbar cortical screw-rod fixation versus pedicle screw-rod fixation with and without interbody support. Spine (Phila Pa 1976). 2013 Apr 15;38(8):635-41.

18. Glennie RA, Dea N, Kwon BK, Street JT. Early clinical results with cortically based pedicle screw trajectory for fusion of the degenerative lumbar spine. J Clin Neurosci. 2015 Jun;22(6):972-5. Epub 2015 Mar 11.

19. Sakaura H, Miwa T, Yamashita T, Kuroda Y, Ohwada T. Posterior lumbar interbody fusion with cortical bone trajectory screw fixation versus posterior lumbar interbody fusion using traditional pedicle screw fixation for degenerative lumbar spondylolisthesis: a comparative study. J Neurosurg Spine. 2016 Nov;25(5):591-5. Epub 2016 May 27.

20. Matsukawa K, Kato T, Yato Y, Sasao H, Imabayashi H, Hosogane N, Asazuma T, Chiba K. Incidence and risk factors of adjacent cranial facet joint violation following pedicle screw insertion using cortical bone trajectory technique. Spine (Phila Pa 1976). 2016 Jul 15;41(14):E851-6.

21. Chen Z, Zhao J, Xu H, Liu A, Yuan J, Wang C. Technical factors related to the incidence of adjacent superior segment facet joint violation after transpedicular instrumentation in the lumbar spine. Eur Spine J. 2008 Nov;17(11):1476-80. Epub 2008 Sep 16.

22. Cardoso MJ, Dmitriev AE, Helgeson M, Lehman RA, Kuklo TR, Rosner MK. Does superior-segment facet violation or laminectomy destabilize the adjacent level in lumbar transpedicular fixation? An in vitro human cadaveric assessment. Spine (Phila Pa 1976). 2008 Dec 15;33(26):2868-73.

23. Park P, Garton HJ, Gala VC, Hoff JT, McGillicuddy JE. Adjacent segment disease after lumbar or lumbosacral fusion: review of the literature. Spine (Phila Pa 1976). 2004 Sep 1;29(17):1938-44.

24. Mobbs RJ. The "medio-latero-superior trajectory technique": an alternative cortical trajectory for pedicle fixation. Orthop Surg. 2013 Feb;5(1):56-9.

25. Analiz Rodriguez A, Neal MT, Liu A, Sundaram AS, Hsu W, Branch Jr. CL. Novel placement of cortical bone trajectory screws in previously instrumented pedicles for adjacent-segment lumbar disease using CT image-guided navigation: technical note. Neurosurg Focus. 2014;36(3):E9.

26. Calvert GC, Lawrence BD, Abtahi AM, Bachus KN, Brodke DS. Cortical screws used to rescue failed lumbar pedicle screw construct: a biomechanical analysis. J Neurosurg Spine. 2015 Feb;22(2):166-72. Epub 2014 Dec 5.

27. Snyder LA, Martinez-Del-Campo E, Neal MT, Zaidi HA, Awad AW, Bina R, Ponce FA, Kaibara T, Chang SW. Lumbar spinal fixation with cortical bone trajectory pedicle screws in 79 patients with degenerative disease: perioperative outcomes and complications. World Neurosurg. 2016 Apr;88:205-13. Epub 2015 Dec 30.

28. Lee GW, Son JH, Ahn MW, Kim HJ, Yeom JS. The comparison of pedicle screw and cortical screw in posterior lumbar interbody fusion: a prospective randomized noninferiority trial. Spine J. 2015 Jul 1;15(7):1519-26. Epub 2015 Feb 26.

29. Ninomiya K, Iwatsuki K, Ohnishi Y, Yoshimine T. Radiological evaluation of the initial fixation between cortical bone trajectory and conventional pedicle screw technique for lumbar degenerative spondylolisthesis. Asian Spine J. 2016 Apr;10(2):251-7. Epub 2016 Apr 15.

30. Mori K, Nishizawa K, Nakamura A, Imai S. Short-term clinical result of cortical bone trajectory technique for the treatment of degenerative lumbar spondylolisthesis with more than 1-year follow up. Asian Spine J. 2016 Apr;10(2):238-44. Epub 2016 Apr 15.

31. Matsukawa K, Yato Y, Kato T, Imabayashi H, Asazuma T, Nemoto K. Cortical bone trajectory for lumbosacral fixation: penetrating S-1 endplate screw technique: technical note. J Neurosurg Spine. 2014 Aug;21(2):203-9. Epub 2014 Apr 25.

32. Matsukawa K, Yato Y, Hynes RA, Imabayashi H, Hosogane N, Asazuma T, Toshiyasu M, Kobayashi Y, Nemoto K. Cortical bone trajectory for thoracic pedicle screws: a technical note. Clin Spine Surg. 2016 Jun 20. [Epub ahead of print].