Original Article

Robotic-assisted Spine Surgeries: An Analysis of 750 Cases from Occiput to Sacrum

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Abstract

Background: Most studies conducted by early adopters of the third generation robotic-assisted pedicle screw placement systems have predominantly focused on the placement of thoracolumbar pedicle screws. The current study is a report on 750 cases of robotic assisted spine surgery, for varied etiologies from the occiput to the sacrum in all manner of spine surgeries.

Materials and Methods: In a prospective study, the 750 consecutive patients who underwent robotic-assisted screw insertion using MazorX Stealth Edition (Medtronic Ltd, Dublin, Ireland) were included. Thus, 4921 implants placed from occiput to ilium. The demographic and surgical details of all patients was noted and postoperative O-arm scans were done to determine accuracy of implants.

Results: In the current series, total of 4921 posterior spinal anchors were implanted, including 443 cervical pedicle screws, 15 cervical lateral mass screws, 4457 thoracolumbar pedicle screws (with 58 S2AI screws), and 6 ilio-sacral screws. 74 vertebrae received bone cement augmentation. 10 robotically inserted screws were revised due to unacceptable pedicle breaches. The overall clinical acceptability of screws was 99.8%. Analysis of preoperative plans and postoperative O-arm scans revealed no statistically significant differences between planned and executed screw trajectories.

Conclusion: The third generation robotic-assisted pedicle screw placement system along with intraoperative 3-D O-arm imaging is useful in safe and accurate placement of posterior spinal anchors in cervical and thoracolumbar spine.

Keywords: Cervical spine, pedicle screw, robotic spine surgery, thoracolumbar spine

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INTRODUCTION

While surgical techniques and technologies have advanced, the indications and principles of spine surgery have remained the same over the years. From the era of open

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surgery that comprised wide exposures, extensive soft-tissue dissection, and prolonged hospitalization, to minimally invasive surgeries using navigation guidance that allowed for minimal soft-tissue dissection and enhanced recovery following spine surgery, technology has helped improve patient outcomes.[1-3] Spine robots were developed with the goal of placing thoracolumbar pedicle screws; however, their ability to drill accurate trajectories with a narrow margin for error allows their use beyond placing spinal anchors.[4-6]

The third-generation spine robots utilize the robotic arm to guide the drilling of trajectories in the bone while providing visual feedback with navigation assistance. The intraoperatively acquired cone-beam computed tomographic (CT) scan after positioning the patient on the operating table is likely to give better accuracy with respect to the intervertebral anatomy as compared to the use of preoperative CT scans done in the supine position. The robotic arm restricts the surgical instruments to 2º of freedom and ensures that the drill, tap, and screws are placed only along the planned trajectory. The addition of navigation ensures visual feedback throughout the preparation of the screw track and allows screws to be inserted to the planned depth.[7] The navigable high-speed burr that can be used in conjunction with the spine robot also allows for visualization of critical adjacent structures during vertebral column resection.

Most studies conducted by early adopters of the third-generation robotic-assisted pedicle screw placement systems have predominantly focused on the placement of thoracolumbar pedicle screws and their accuracy.[8-11] The objective of this study is to report our experience with 750 consecutive cases of robot-assisted spine surgery. These cases (49 of which were posterior cervical spine surgeries and 698 were thoracolumbar spine surgeries, 3 of which were vertical shear injuries of the pelvis) encompassed diverse etiologies, with instrumentation performed via a posterior approach from the occiput to the sacrum. The study aims to evaluate the accuracy of this technique across the spectrum of spinal surgeries.

MATERIALS AND METHODS

Institutional ethical committee clearance was obtained before the commencement of the study. In a prospective study, the 750 consecutive patients who underwent robotic-assisted screw insertion using MazorX Stealth Edition (Medtronic Ltd, Dublin, Ireland) were included. Thus, 4921 implants placed from occiput to ilium, including 58 S2 alar iliac (S2AI) screws and 6 Ilio-Sacral screws formed the basis of this study.

Robotic-assisted surgical technique

Our 55m^2 operating room accommodates the robot, O-arm, table, and anesthesia. We used "scan and plan" workflow with intraoperative imaging. Adequate OR space and minimal clutter are crucial for O-arm movement. All spinal deformity cases had multimodal neuromonitoring. For lumbar cases, the robot was mounted to the patient semi-rigidly using a Schanz pin on the left posterior superior iliac spine. In thoracic and deformity cases, we initially used a Schanz pin but later discontinued it. Spinous process clamps were found cumbersome. Self-retaining retractors remained during O-arm scans. Thoracic transverse processes, hypertrophied lumbar facets, and cervical lateral masses were flattened before registration. The robot scans the area using infrared and optical cameras to define "no-fly-zones." "Snapshot" registration is repeated if accuracy is lost. The blunt passive planar probe is placed in the region of interest, and the "star-marker" fiduciary array is attached to the robotic arm.

The O-arm is brought in, and the surgical field is covered with a disposable plastic drape. We ensure all four "star-marker" beads are visualized on the 3D scan. The system uses the "star-marker" to locate vertebrae. The standard O-arm scan's field of view is 15 cm, increased to 40 cm for wider visualization (e.g., S2AI screws).

The O-arm images are sent to the robotic workstation for automatic vertebral segmentation. Ensure both pedicles are visualized in each segment. Anteroposterior view segmentation is crucial for thoracolumbar deformity correction, and the lateral view is important for lumbar degenerative surgeries. Screw planning ensures intraosseous placement in all three planes.

The 3 mm × 30 mm high-speed drill creates the entry into the pedicle. An appropriate tap is selected. Pedicle screws are either placed directly through the robotic arm-guide or over guide wires. Separate lateral incisions are used for lumbar pedicle screws in short-segment fixation, with a single incision allowing up to four screws. Central levels are instrumented first in long segment instrumentation, followed by end levels with separate lateral or subfascial/submuscular incisions to minimize soft-tissue pressure on the robotic arm.

For S2AI screws, muscular dissection distal to the S1 foramen is unnecessary. The 3 mm × 30 mm high-speed drill creates the initial track, followed by the 4 mm × 60 mm and 6.5 mm × 60 mm taps.

During posterior cervical surgery, the patient is positioned on the radiolucent operating table with the head secured using Mayfield tongs. Due to the absence of safe bony prominences near the cervical spine, direct connection of the robot to the patient is not feasible. Care is taken to minimize patient movement.

A second O-arm scan is taken in cases requiring longer level instrumentation, loss of accuracy not rectified by reacquiring "snapshot," and arm shift caused by excessive pressure on the robotic arm.

Demographic and etiological data of all patients were noted. The cut-to-close time (total time elapsed from the initial skin incision to the closure of the surgical site), time per screw (average time taken to insert each pedicle screw), O-arm time (time the O-arm was positioned for anteroposterior fluoroscopy image until completion of acquisition of the 3D fluoroscopic image), robot time (the time of mounting of the robot until completion of insertion of the last screw/guide-wire), and blood loss were noted in all cases.

Following the procedure, an O-arm scan was taken in all patients to determine screw placement and the presence of breach, which were graded as described by Gertzbein and Robbins.[12] The planned and executed trajectories of all posterior spinal anchors were overlapped using Digimizer

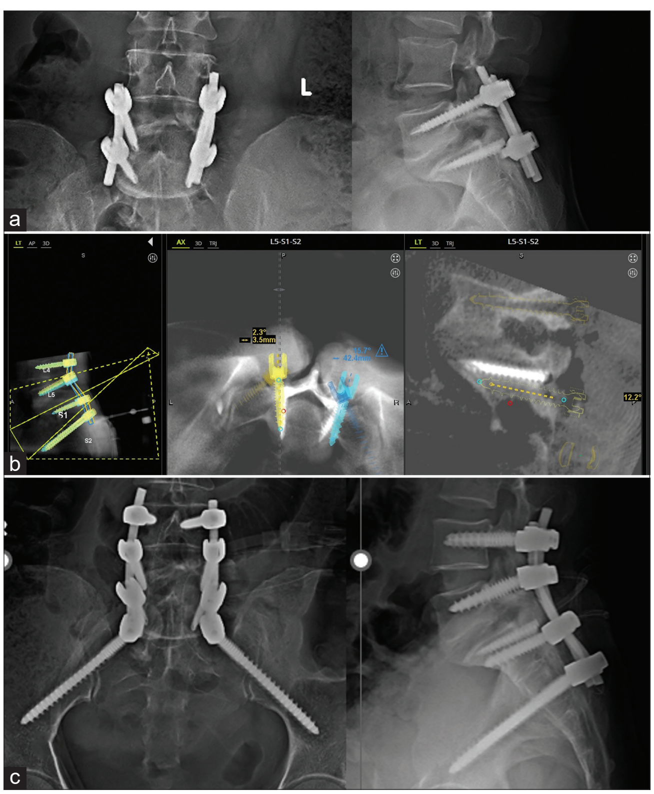

Figure 1: Preoperative radiographs showing L5-S1 Fusion with broken implants (a). The S1 screws were planned bypassing the broken implants (b) and postoperative radiographs showing well positioned implants (c)

version 5.0 to determine if there was a difference in planned and executed trajectories [Figure 1]. All patients were mobilized within 6 h after surgery.

Statistical analysis

The quantitative data were expressed as mean ± SD, and qualitative data were expressed as percentage. The unpaired t-test, Mann–Whitney U test, was used to compare means and the Chi-square test was used to compare frequencies. A $P < 0.01$ was considered statistically significant.

RESULTS

The descriptive statistics of the patients are shown in Table 1. In the current series, 4921 posterior spinal anchors were placed. This included 443 cervical pedicle screws in 46 patients, 15 cervical lateral mass screws in 3 patients, 4457 thoracolumbar pedicle screws (including 58 S2AI screws) [Figure 2] in 636 patients, and 6 ilio-sacral screws in 3 patients. In addition, 74 vertebrae were augmented with bone cement in 62 patients.

The mean cut-to-close time was 187 ± 124 min, the mean time per screw was 3.5 ± 1.2 min, the mean O-arm time was 6.8 ± 3.2 min, the mean robot time was 21.3 ± 11.2 min, and the mean blood loss was 314.2 ± 128 mL. The data specific to posterior cervical spine surgeries is shown in Table 2. Ten screws inserted with robotic assistance were revised due to intraoperatively detected clinically unacceptable (G and R C to E) pedicle breaches. The frequency of clinically acceptable screws in the current study was 99.8%. Eighteen patients had superficial infections that settled with antibiotics and regular dressings, and two patients had deep infections that required re-exploration and wound wash.

Table 1: Descriptive statistics of studied sample

	Robotic-assisted spine surgeries (*n*=750)
Age (years), mean±SD	55.3±24.6
Frequency of females	56%
BMI (mean±SD)	29.1±3.8
Mean cut to close time (min)	187±124
Mean robot time (min)	21.3±11.2
Mean O-arm time (min)	6.8±3.2
Mean time per screw (min)	3.5±1.2
Blood loss in mL (mean±SD)	314.2±128

SD: Standard deviation, BMI: Body mass index

Table 2: Details of robotic assisted cervical surgeries

	Number of surgeries (*n*=49)
Mean surgical time (min)	214±32
Mean robot time (min)	33±6
Mean O-arm time (min)	7
Mean time per screw (min)	3
Blood loss (mL), mean±SD	232±115

SD: Standard deviation

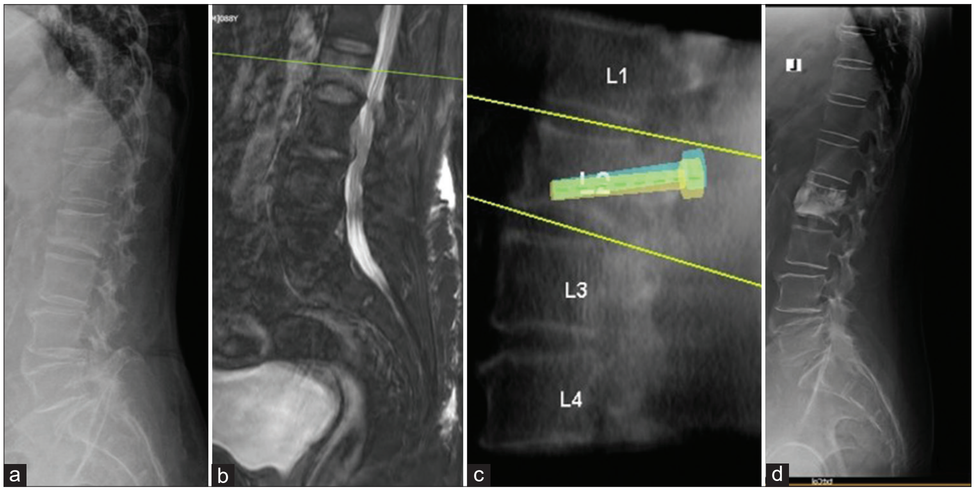

Figure 2: Preoperative radiograph and magnetic resonance imaging (a and b) of a patient with L2 inferior endplate fracture. The trajectory was directed to the site of fracture (c), postoperative radiographs showed no leak in cement into the canal (d)

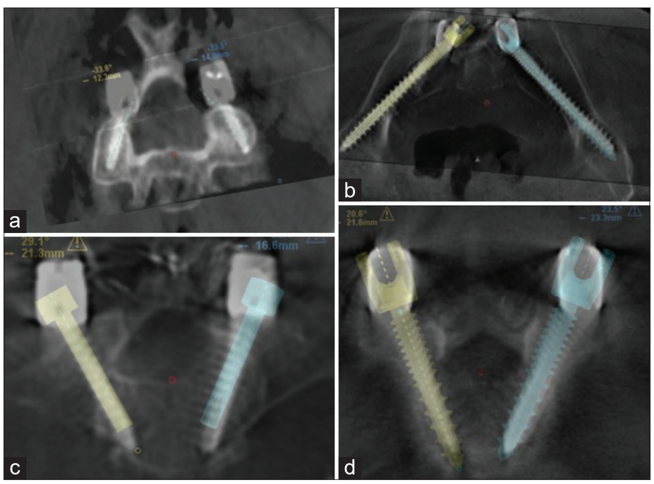

Figure 3: Overlapped images of planned and executed trajectories of lateral mass screws (a), S2 alar iliac screws (b), thoracic pedicle screws (c), and lumbar pedicle screws (d) showing minimal deviation

One patient developed cauda-equina syndrome secondary to epidural hematoma. None of the patients developed any permanent postoperative neurological deficits.

In patients who underwent vertebral cement augmentation (Kyphoplasty) [Figure 3], the frequency of cement leak was 14%, but none of it was into the canal, vertebral height increased from 58.1 ± 35.5-94.9 ± 27.1 and segmental kyphosis decreased from 25.5 ± 7.2–7.2 ± 4.3 [Table 3].

The mean length of stay was 1.2 days, and the 90-day reoperation rate was 0.83%.

There were no statistically significant differences in the planned and executed trajectories, as evidenced by comparing the angle of insertion from preoperative plans and postoperative O-arm scans.

DISCUSSION

Previous studies on the learning curve associated with robotic-assisted spine surgery showed the success rate of pedicle screw placement had a plateauing effect after thirty cases. In the current study, there was no significant difference in the O-arm time, blood loss, robot time, and time per screw, with the times being comparable to that shown in other studies.[7] The cut-to-close time was also found to be higher in the first few cases. This is similar to the findings of Khan *et al.*, and can be explained by the time taken for the surgical team to get used to the newer robotic workflows.[7]

In the current study, the accuracy of screw placement was 99.8%, with reports in literature ranging from 91 to 99%.,[7-11] While in theory, the robotic arm restricts movement to 2° of freedom, subtle movement of the arm guide can occur due to soft-tissue pressure. In short constructs in the lower lumbar spine, this can be negated by placing separate incisions for screw placement while using the midline incision only for decompression. As the craniocaudal trajectories converge, typically 3–4 screws can be inserted through a single planned stab incision [Figure 4]. We also recommend flattening of the thoracic transverse processes using a bone rongeur, before "scan and plan" as the slope can cause the arm guide and instruments to skid medially. We prefer adequate-length skin incisions in constructs spanning four or more segments in the thoracic spine and leave the self-retaining retractors in place during the O-arm scan. This allows the placement of the arm guide and sleeve with minimal soft-tissue pressure on the bone. Submuscular, subfascial, or separate stab incisions can be used for screws at the upper and lowermost instrumented vertebrae in those cases where we are unable to place the

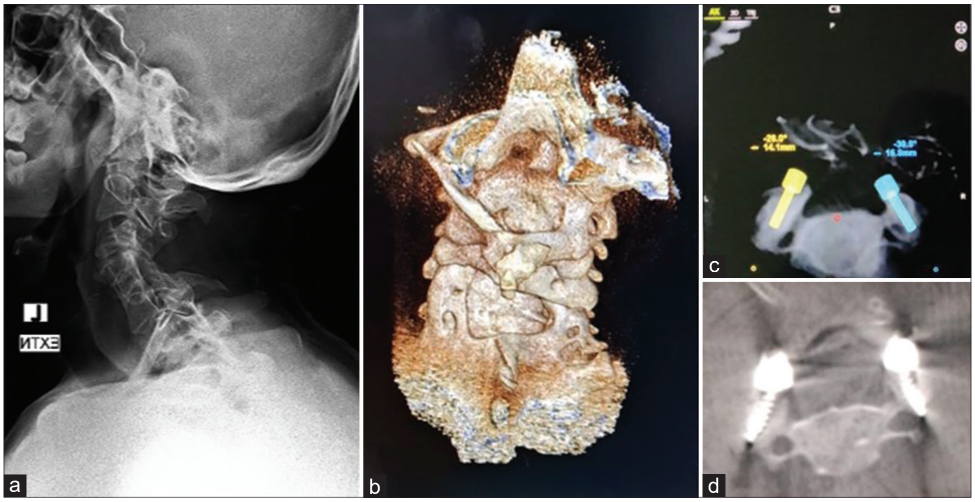

Figure 4: Preoperative radiographs (a) and computed tomography (b) of a patient with Klippel Feil syndrome with previous cervical laminectomy showing significantly altered anatomy. Screenshot of robotic workstation showing planning of lateral mass screw in the presence of altered anatomy (c). Postoperative computed tomographic scan showing well placed lateral mass screw (d)

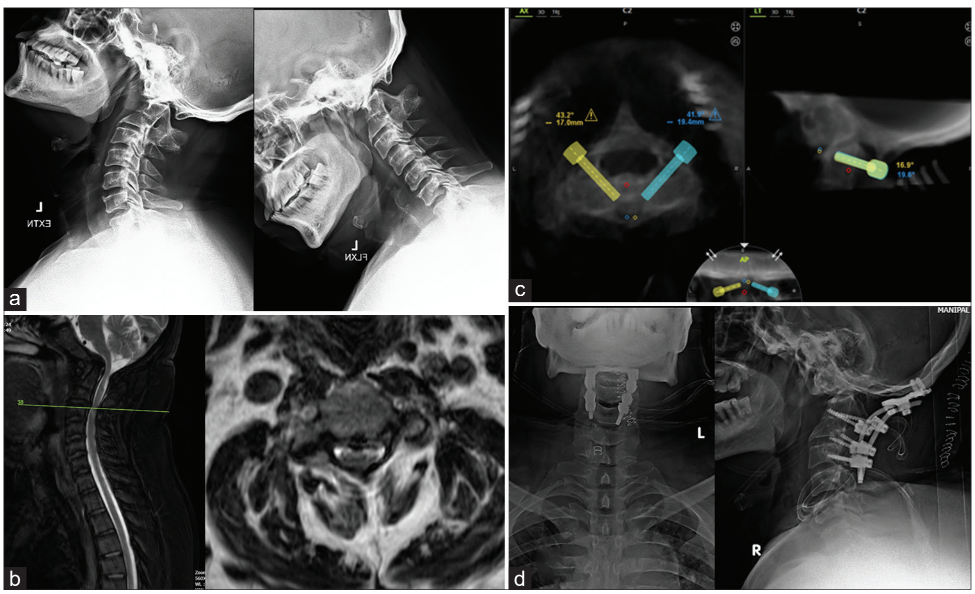

Figure 5: Preoperative radiographs (a) and magnetic resonance imaging (b) of a patient with basilar invagination. Screenshot of C2 pedicle screw planning (c) and post-operative radiographs following occipito-cervical fusion (d)

sleeve directly on the bone. The ideal sequence of screw placement is zigzag, starting away from and moving toward the reference frame as navigational accuracy decreases over time.

Pearls and pitfalls

In all patients, the robot was mounted on the right side of the prone patient, and therefore, the posterior superior iliac spine bone mount in all patients was placed on the left. This not only familiarized nursing staff to the workflow but also ensured that the robotic arm was placed at an obtuse angle at the shoulder as required for the prone workflow. While positioning the star marker before the O-arm scan, it is important to ensure that the elbow is on the right. This is especially important in obese patients as the bone mount will get in the way of the "star marker" being close to the patient, which will result in poor O-arm images. Keen attention must be paid at every step of the procedure as a small mishap, such as malposition of the arm guide at the start of the surgery, can have harmful consequences during surgery. Inadvertent patient shift or reference frame shift during the surgery can result in inaccuracies in navigation. Therefore, it is important to verify navigation accuracy at different times in the procedure with the blunt passive planar probe. When in doubt, reacquire the "snapshot" (robot arm registration by navigation) to restore navigation accuracy. However, if the loss of navigation accuracy persists, rescanning of the patient may be necessary.

Table 3: Details of robotic assisted Balloon Kyphoplasty

	Robot-assisted Balloon Kyphoplasty (*n*=74)
Preoperative vertebral height (percentage of expected height)	58.1±35.5
Postoperative vertebral height (percentage of expected height)	94.9±27.1
Preoperative segmental kyphosis	25.5±7.2
Postoperative segmental kyphosis	7.2±4.3
Frequency of cement leak	14%

It is important to tap the far cortex during the preparation of the S1 screw track when not using awl-tipped screws. While acquiring images for S2 alar iliac screws, the field-of-view of the O-arm scan needs to be increased to 40 cm to adequately visualize the pelvic anatomy. During placement of the S2 alar iliac screw, there is a risk of skiving and bending of the tap at the cortical bone of the sacroiliac joint; therefore, it is important to use the 4 mm awl-tipped tap first, followed by the 6.5 mm awl-tipped tap.

The third-generation robot can also be paired with a navigated high-speed burr which is useful in cases where posterior transpedicular decompression, vertebral column resection, and pedicle subtraction osteotomies are planned. The advantages include less bleeding during the osteotomy and visualization of critical surrounding structures, which cannot be seen directly during the procedure.

In the cervical spine, to mitigate the risk of inadvertent damage to critical structures, we ensured that the "feather touch" drill, equipped with a stopper at a depth of 30 mm and a length of 150 mm, was placed at the height of 170 mm. This precautionary measure limited the drill's penetration of the lateral mass to no more than 10 mm and prevented it from inadvertently plunging anteriorly. In addition, this positioning facilitated visualization of the entry point, ensuring that there was no excess pressure on the arm guide or loss of navigational accuracy.

While previous feasibility studies in cadavers investigated the placement of cervical pedicle screws using multiple separate lateral incisions at each level, the placement of lateral mass screws was possible through the midline incision used for decompression in most cases.[13] Separate lateral incisions were needed at the most caudal level in patients with cervical kyphosis. The spinous processes were removed before the O-arm scan as they came in the way of the trajectory and severe spondylosis, the convex lateral mass needed to be flattened to ensure bicortical screw placement [Figure 5].

The robotic system can be utilized to drill trajectories for the insertion of trocar and kyphoplasty balloons, especially in challenging situations such as obesity, osteoporosis, and deformity, without creating multiple tracks.[14,15] The system also allows for the direction of the trajectory toward specific areas like inferior- or superior endplate fractures. The single entry in these patients reduces the risk of cement leakage into the canal and allows precise placement of bone cement.

CONCLUSION

The third-generation robotic-assisted pedicle screw placement system, along with intraoperative 3-D O-arm imaging, is useful in safe and accurate placement of posterior spinal anchors and can substitute for a navigation system during anterior cervical surgery. While a learning curve exists while adopting this new technology, it builds on existing systems, and surgeons can draw on previous experience to develop workflows that are conducive to them. Cautious and judicious use of robotic guidance in experienced surgical hands with the anatomical orientation of the pedicle in mind, the bony feel of the drill, tap, and screw traversing the vertebra is of paramount importance.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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