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Progress of the Anterior Transpedicular Screw in Lower Cervical Spine: A Review

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The anterior transpedicular screws (ATPS) fixation is a valuable discovery in the field of lower cervical spine (LCS) reconstruction, as it has the advantages of both anterior and posterior approaches. In recent years, with in-depth research on ATPS fixation related to anatomy, biomechanical tests, and clinical applications, its firm stability and excellent biomechanical properties have been recognized by more and more surgeons. Although ATPS fixation has been gradually applied in clinic settings under the promotion of emerging distinctive instruments, its long-term efficacy still needs to be further clarified due to the lack of large sample size studies and long-term follow-up. Nevertheless, it is believed that with the maturity of digital devices and the development of precision medicine, ATPS fixation has a promising prospect.

MeSH Keywords: **Bone Screws • Computers • Neurosurgery • Spine**

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Background

Degeneration, trauma, and infection of the lower cervical spine (LCS) often occurs in the anterior column of vertebral bodies [1,2], and the traditional anterior approach with vertebral plate and screw fixation tends to be one of the optional therapies, clinically. However, in patients with poor bone conditions or who need multi-segmental decompression and reconstruction, it is often difficult for traditional anterior fixation to provide sufficient biomechanical stability, which may result in early internal fixation failure or bone graft non-fusion [3–5]. For patients with cervical osteoporosis, tuberculosis, or tumor invasion, the incidence of loosening, prolapse, and break of internal fixations after the traditional anterior cervical vertebral screw fixation is as high as 20% to 50% [4,5]. Moreover, for multi-segmental anterior cervical plate and screw fixation, the incidence of non-fusion can reach 20% to 50%, and the failure rate of internal fixations is also reported to be as high as 30% to 100% [6]. Hence, an additional posterior surgery or postoperative external fixation is necessary to improve early and long-term stability [7,8], which also increases the risk of surgery and infection to a certain extent [9].

Anterior transpedicular screw (ATPS) fixation, proposed by Koller et al. in 2008, has the advantages of both anterior and posterior approaches [10]. Meanwhile, ATPS fixation is also able to effectively avoid the incidence of loosening, prolapse, and breaking of internal fixations [9,10]. Furthermore, it can further compensate for the defects of insufficient vertebral screw holding force in patients with poor bone conditions and provide firmer biomechanical stability [10]. The surgical procedure of ATPS fixation is mainly based on guiding methods to insert screws from the anterior approach through the pedicle. On one hand, it not only takes advantage of excellent stability of pedicle screws fixation, but also can deal with lesions of the vertebral body and intervertebral disc through an anterior approach. On the other hand, it is also able to provide better 3-column stability and reduce surgical trauma and operative time [9,11,12]. Moreover, in addition to the ATPS fixation, posterior pedicle screw and cortical bone trajectory (CBT) screw insertion technology are also alternative methods to be applied to patients with poor bone conditions [13,14]. However, previous studies found that ATPS fixation has a high risk of screw insertion, with a certain possibility of catastrophic complications such as the injuries to the vertebral artery, spinal cord, and nerve roots [9,10]. Thus, the accuracy of ATPS insertion is particularly crucial. This manuscript systematically reviewed the anatomical studies, biomechanical studies, distinctive instruments, and new progress in clinical applications of ATPS fixation, and pointed out the main drawbacks and urgent need for improvements in current clinic settings.

Anatomical Study

ATPS fixation refers to the insertion of screws from the front of the vertebral body to the pedicles; the screws hold the cortical bone of pedicles to obtain the biomechanical stability [10]. However, due to the lack of apparent bony markers in front of the vertebral body, the process of screw insertion may injure the adjacent nerves and vessels, and this technique has long been a challenge for spine surgeons. Moreover, Dong et al. [15] conducted an anatomical measurement of 42 LCS specimens to summarize the 3 key elements of successful ATPS insertion: the accurate entry point, suitable direction, and appropriate specifications of screws (Figure 1).

Koller et al. [10] measured the cervical spine images of 29 healthy people and found that the mean width of lower cervical pedicles increased gradually from the top to bottom, while the mean height changed irregularly, with the smallest at C5. In addition, the camber angle increased gradually from C3 to C5 and decreased from C6 to C7, while the head inclination angle increased gradually from C3 to C7. Moreover, Xu et al. [16] conducted an anatomical study to recommend the ideal way of ATPS fixation. The entry point was set near the anterior midline of the vertebral body and about 5.0 mm away from the upper endplate. In this insertion process, the camber angle from C3 to C5 was about 45.7° to 52.1°, and about 47.8° to 44.4° from C6 to C7. Besides, the head inclination angle from C3 to C6 was about 3.4° to 22.1°, and the C7 was about 12.7°. Wang et al. [6] performed an anatomical study using computed tomography (CT) images of 100 healthy adult cervical spines, and concluded that the entry points of C3 and C4 were located on the opposite side of pedicle, while the entry points of C5 to C7 were located on the same side of pedicle. In summary, the comparisons of the entry points, directions, and recommended screw specifications in the aforementioned ATPS fixation anatomical studies are shown in Table 1.

Based on anatomical studies, it can be concluded that the anatomical morphology of pedicles varies significantly, and the results obtained from different centers are also quite different. Thus, it is difficult to summarize the universal screw insertion parameters. Besides, it is also necessary for spine surgeons to adopt an appropriate insertion method according to the individual preoperative images and intraoperative actual conditions.

Biomechanical Study

The biomechanical advantages of ATPS fixation make it an optional method for multi-segmental LCS reconstruction. According to a biomechanical test performed by Koller et al. [17], the mean pullout force of ATPS fixation group was 467.83 ± 125.76 N,

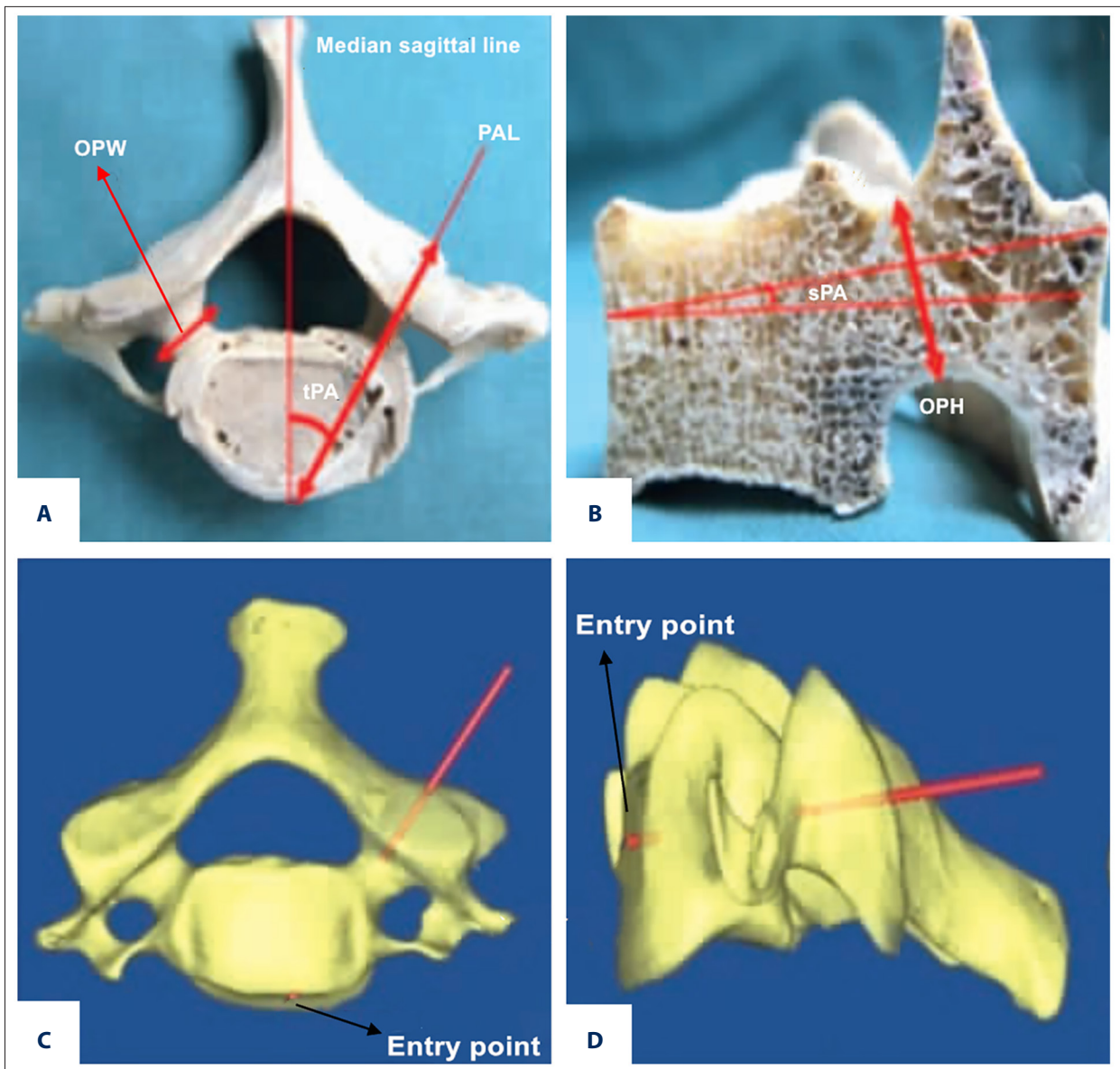


Figure 1. Anatomical illustrations of ATPS fixation. (A) Coronal view of lower cervical spine pedicle. (B) Sagittal view of lower cervical spine pedicle. (C) Coronal view of ATPS fixation. (D) Sagittal view of ATPS fixation. ATPS – anterior transpedicular screws; OPW – out pedicle width; PAL – pedicle axis length; tPA – transverse pedicle angle; OPH – Out pedicle height; sPA – sagittal pedicle angle.

the mean pullout force of ordinary vertebral body screws group was 181.55 ± 82.57 N, and the ATPS fixation group was 2.5 times greater than that of the vertebral body screws (VBS) group. Subsequently, Koller et al. [18] fixed and reconstructed the LCS models of the multi-segmental vertebral subtotal resection using different methods and compared the anti-fatigue tests. It was concluded that the single ATPS fixation and the combined anterior and posterior fixation both had the excellent biomechanical stability, and ATPS fixation provided a similar posterior fixation stability in multi-segmental lesions. Chen et al. [19] applied finite element analysis (FEA) to

verify that the overall biomechanical properties of ATPS fixation were superior to that of ordinary VBS fixation. Wu et al. [4] performed a biomechanical test on 60 LCS specimens and compared the difference of pullout force between the ATPS fixation and ordinary VBS fixation before and after the fatigue tests. Furthermore, the vertebral screw canals were repaired and strengthened with bone cement, and then compared again. The results indicated that the pullout force of ATPS fixation was superior to that of ordinary VBS fixation before and after the anti-fatigue tests, and it was also superior to the VBS strengthened with the bone cement. Thus, it can be concluded

Table 1. Comparison of anterior transpedicular screws parameters in different anatomical studies.

Researchers	Sample size (n)	Entry point		Angle of screws insertion		Screws specifications	
		Distance to upper endplate (mm)	Distance to anterior midline (mm)	Head inclination angle (°)	Camber angle (°)	Diameter (mm)	Length (mm)
Dong et al. [15]	42	5.89~8.35	-2.91~4.82	-11.46~8.59	35.38~46.55	3.5	28~32
Koller et al. [10]	29	3.02~6.86	-1.21~2.77	4.09~21.18	40.21~52.03	3.5/4.5	34~36
Xu et al. [16]	20	3~6	-1.97~3.98	3.4~22.1	45.7~52.1	3.5/4.0	32
Wang et al. [6]	100	6~8.5	-5~3	-12~13	40~49	3.5/4.5	30~34

The entry point and angle of screws insertion were recorded as positive values on the opposite side of the pedicle and as negative values on the same side.

Table 2. Different biomechanical studies and results of anterior transpedicular screws fixation in lower cervical spine (C3–C7).

Researchers	Research samples	Sample size (n)	Research trails	Research conclusions and significance
Koller et al. [17]	ATPS versus VBS	ATPS (n=23) VBS (n=22)	Mechanical tests	The mean pullout force of ATPS fixation group was 2.5 times greater than that of VBS fixation group
Koller et al. [18]	ATPS versus SAPI	ATPS (n=6) SAPI (n=6)	Anti-fatigue tests	The ATPS fixation provided a similar posterior fixation stability in multi-segmental lesions
Chen et al. [19]	ATPS versus VBS	N/A	Finite element analysis	The overall biomechanical properties of ATPS fixation were superior to that of ordinary vertebral screws fixation
Wu et al. [4]	ATPS versus VBS	N/A	Mechanical and anti-fatigue tests	The pullout force of ATPS fixation was superior to that of VBS fixation before and after anti-fatigue tests, and was also superior to the VBS fixation strengthened with bone cement

Measurement methods regarding the pullout force: the screws were pulled out at a rate of 5 mm/minute by a material testing machine along the longitudinal axis of screws, and each pullout force was recorded by a computerized data collection system. ATPS – anterior transpedicular screws; VBS – vertebral body screws; SAPI – standard anteroposterior instrumentation; N/A – not applicable.

from the biomechanical studies that ATPS fixation not only shows excellent immediate stability, but also the long-term stability. Different biomechanical studies and results of ATPS fixation are summarized in Table 2.

Distinctive Instruments for ATPS Fixation

In early stages, due to the lack of distinctive instruments for ATPS fixation, the AXIS plates and AO reconstruction plates were mostly used as the substitutes [9,20,21]. In the clinic, Zhao et al. [21] found that postoperative dysphagia in a few patients might be related to the apparent protrusion of plates and screws on the bone surface. The fixed screw hole spacing might not be suitable for the LCS with varied anatomical

changes, and the excessive length of plates might also accelerate the degeneration of adjacent segmental intervertebral discs. Furthermore, since ATPS fixation is required to be inserted at a large inclined angle, the conventional instruments are difficult to use to meet this requirement, and a protruding screw tail also has a potential risk of esophageal complications [22–25]. Hence, more and more attention has been attached to the research and development of distinctive instruments for ATPS fixation.

Zhao et al. [26] designed a distinctive plate system for ATPS fixation with a pair of screw holes on the upper and lower ends of the plate, thus, a pedicle screw and a VBS can be inserted. The screw holes have locking pieces, and the cross section and longitudinal section of plate are arc-shaped, which

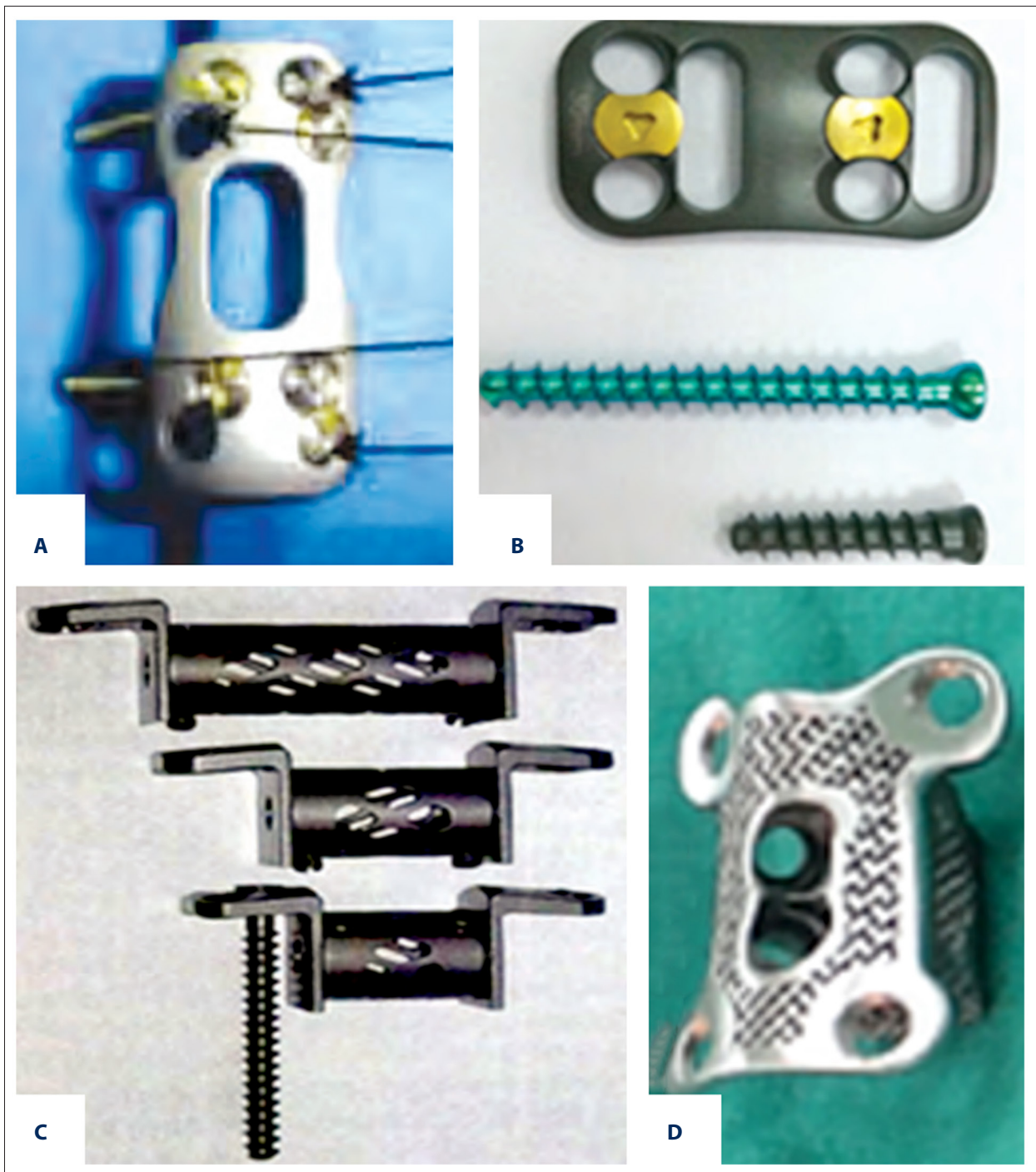


Figure 2. The distinctive instruments for ATPS fixation. (A) Designed by Zhao et al. [26]. (B) Designed by Zhang et al. [11]. (C) Designed by Wu et al. [27]. (D) Designed by Zhang et al. [28]. ATPS – anterior transpedicular screws.

increases the matching between the plate and vertebral body. Zhang et al. [11] successfully applied a new type of anterior pedicle screw and plate system to 12 patients with cervical dislocation and realized the simultaneous insertion of ATPS in the bilateral pedicles of the same vertebral body. The upper and lower ends of this device are respectively provided

with a set of screw holes, including the upper pedicle screw holes and lower 2 vertebral screw holes, and the VBS hole has a locking piece. Wu et al. [27] designed an artificial vertebral body with ATPS and compared it with the common anterior titanium and mesh system by the FEA. It was concluded that the stability of artificial vertebral body in the fixed segments

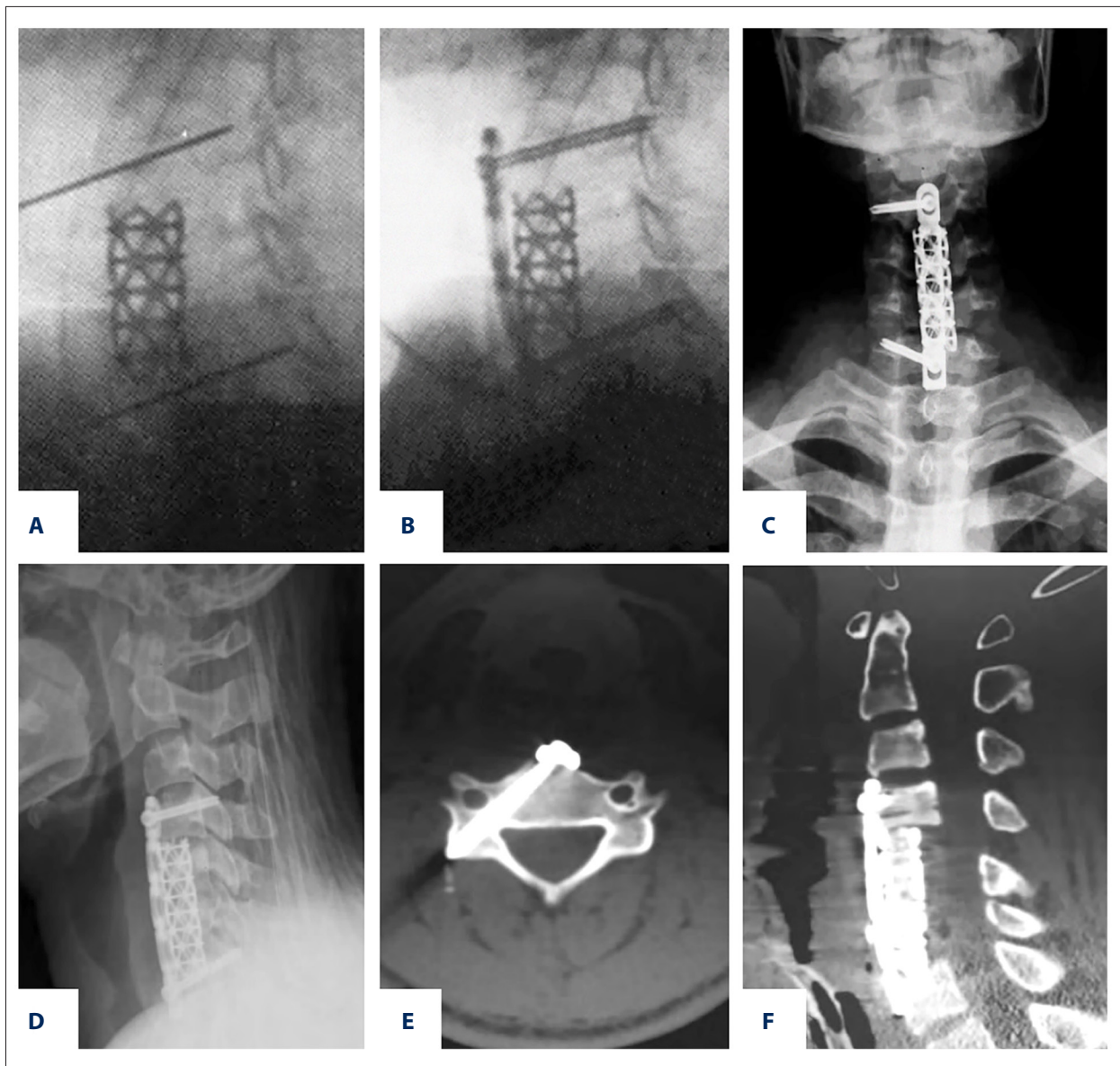


Figure 3. Clinical application case with intraoperative and postoperative radiographs. **(A)** Intraoperative C-arm x-ray showed the direction of K-wire was accurate. **(B)** C-arm x-ray showed the satisfactory insertion of pedicle screws, titanium mesh and plate. **(C, D)** Postoperative cervical spine x-rays showed suitable internal fixation position (**C**: anterior view, **D**: lateral view). **(E)** Postoperative transverse computed tomography (CT) showed that insertion of pedicle screws was safe and accurate. **(F)** Postoperative sagittal CT showed that insertion of pedicle screws was stable and reliable.

was better than that of the common anterior titanium and mesh system. The stress distribution of the artificial vertebral body was more dispersed and balanced than that of the anterior titanium and mesh system, and the risks of internal fixation fracture and implant subsidence might be lower. In addition, Zhang et al. [28] designed and applied a new type of 3-dimensional (3D) printing assisted anterior bilateral pedicle screws fixation of the artificial vertebral body to a patient with cervical tuberculosis and obtained excellent clinical outcomes and realized the ultra-short segment fixation of the

diseased vertebrae. Besides, compared with the conventional titanium and mesh group by the FEA, it was found that the fixation stress of artificial vertebral body group was more uniformly dispersed and balanced, which could effectively prevent the degeneration of adjacent vertebral bodies and intervertebral discs. The aforementioned distinctive instruments for ATPS fixation are shown in Figure 2, and the clinical application case with intraoperative and postoperative radiographs are presented in Figure 3.

Table 3. Preoperative preparations of anterior transpedicular screws fixation in different studies.

Researchers	Year	Additional preoperative preparations	Role and significance
Koller et al. [17]	2008	Pedicle axial x-ray fluoroscopy	Searching for screw insertion channel and evaluating screw insertion environment
Yukawa et al. [9]	2009	Vertebral artery angiography	Evaluating the location of vertebral artery to prevent the presence of variation
Wang et al. [34]	2012	Three-dimensional reconstruction of cervical spine	Obtaining the individualized screws insertion parameters
Fu et al. [35]	2013	Fabricating the path guide plate	Using the path guide plate to guide the screw insertion

Table 4. Insertion methods of anterior transpedicular screws and accuracy rates in different studies.

Researchers	Year	Insertion methods of screws	Accuracy rates
Koller et al. [17]	2008	X-ray fluoroscopy	Axial position: 78.3% Sagittal position: 95.7%
Koller et al. [29]	2009	Navigation devices	100%
Fu et al. [35]	2013	Individualized path guide plates	91.7%
Bredow et al. [36]	2016	Three-dimensional fluoroscopy navigation system	95%
Patton et al. [37]	2015	X-ray fluoroscopy and navigation devices	X-ray fluoroscopy: 42.6% Navigation devices: 66.7%

Clinical Applications

Indications

In a study, Koller et al. [29] found that ATPS fixation had a larger safe area for screws insertion than the posterior fixation, but there was still a risk of injury to the adjacent important structures. In addition, the indications reported in the literature mainly include: 1) the 3-column injury and instability of single-segment cervical spine; 2) the multi-segmental anterior cervical decompression, reconstruction or renovation; 3) tumors, infections, osteoporosis, rheumatoid arthritis and ankylosing spondylitis requiring the anterior cervical spine decompression and reconstruction; and 4) cervical spine fracture or dislocation requiring the anterior decompression and reconstruction [21,30–32]. Thus, due to the current immaturity of ATPS fixation, it is still not qualified to replace the conventional anterior cervical decompression and fusion (ACDF) and the posterior pedicle screws fixation. However, it can be considered as a supplementary method to increase the stability of anterior fixation and should be selectively applied to the patients with relevant indications.

Preoperative preparations

Due to the varied changes in anatomical morphology of the LCS, it is necessary to improve preoperative imaging examinations,

formulate a strict surgical plan, and apply fluoroscopy reasonably [33]. Yukawa et al. [9] suggested that preoperative vertebral artery angiography should be performed to determine whether to perform surgery on the other side, or to switch to other surgical procedures, or even abandon the surgery due to the presence of dominant or variant vertebral arteries in some patients. Wang et al. [34] recommended the preoperative cervical CT scan and the reconstruction of 3D models with Mimics software to obtain the individualized screws insertion parameters. Thus, in view of the high risk of ATPS fixation, it is essential for spine surgeons to thoughtfully consider the relevant preoperative preparations. In this process, in addition to only focusing on the design of screw paths and the specifications of screws, careful assessment should also be conducted of the screw insertion environment and anatomical characteristics of the patients. Table 3 shows the preoperative preparations of ATPS fixation in the different studies.

Insertion methods of screws

As shown in Table 4 [17,29,35–37] the insertion methods of anterior pedicle screws currently include 4 types: 1) the pedicle axial x-ray fluoroscopy assisted screws insertion, represented by Koller et al. and Yukawa et al. [9,17]; 2) the “in-out-in” technique, using anterior decompression holes to find the opening of the posterior wall of vertebral bodies for pedicle screws insertion, represented by Aromomi et al. [38]; 3) the use of

Table 5. Postoperative complications of anterior transpedicular screws fixation in different clinical studies.

Researchers	Patients (n)	Length of follow-up, month	Postoperative complications, n (%)					
			Dysphagia	Screw penetrating through pedicle	Hoarseness	Vertebral artery injury	Spinal cord injury	Nerve roots injury
Yukawa et al. [9]	6	12.2±4.3	2 (33.3)	0	0	0	0	0
Wang et al. [34]	10	9.1±3.5	2 (20)	0	0	0	0	0
Aramomi et al. [38]	9	12.3±2.7	0	1 (11.1)	0	0	0	0
Zhao et al. [21]	22	15.5±8.6	2 (9.1)	4 (18.2)	1 (4.5)	0	0	0

navigation devices to assist the screws insertion, represented by Koller et al. [29]; and 4) the method of Fu et al. [35] and Li et al. [39] for reconstruction of the individualized 3D structure of the cervical spine based on CT scan data, and with the path guide plate made by rapid prototyping technology to assist screws insertion. At present, the pedicle axial x-ray fluoroscopy is widely applied in clinical settings [9,11], and the screws are inserted with a suitable inclination angle and fixed entry point. However, this method requires strict surgical experience and expert anatomical knowledge. Koller et al. [17] applied the x-ray fluoroscopy to assist screws insertion, and the experimental results indicated that the accuracy rate of the inserted screws in the axial position was 78.3%, and the accuracy rate of the sagittal position was 95.7%. In addition, Koller et al. [29] used the navigation devices to assist screws insertion, with accuracy rate reaching 100%. In this process, under the guidance of electric conductivity devices (ECD), the pedicle screws were able to advance stepwise with small circular movements and the deviations of direction can also be corrected, which guarantees the high accuracy rate of screws insertion. Moreover, Bredow et al. [36] applied a 3D fluoroscopy navigation system to insert 20 anterior transpedicular screws into LCS models, with an accuracy rate of 95%. In this process, an automatic referencing was made with assistance of 3D C-arm, and the pedicle entry point was able to be located with the drill guide. In addition, Fu et al. [35] inserted the screws on 24 LCS specimens via the individualized path guide plates, and the accuracy rate of insertion was 91.7%. Briefly, in this process, the path guide plate was closely attached to the anterior edge of vertebral body and without apparent shaking, and a 2.0 mm K-wire was then inserted into the pedicle. After all pedicle walls were assessed to be unperforated by the probe, anterior transpedicular screw was ultimately inserted into the pedicle. Therefore, in theory, individualized screws insertion with the assistance of various methods is the most ideal way of ATPS fixation.

However, another study showed different results. Patton et al. [37] compared the insertion results of 54 anterior

pedicle screws in 9 LCS specimens assisted by x-ray fluoroscopy and navigation devices respectively. The accuracy rate of insertion was 42.6% in the fluoroscopy group and 66.7% in the navigation group, and the difference between the 2 groups was statistically significant ($P=0.012$). It was thus concluded that the accuracy rate of the navigation group was higher than that of the fluoroscopy group, but there was still a certain rate of poor insertion in both groups. Hence, it is necessary to promote further anatomical and imaging research and ensure a safer insertion environment before clinical applications.

Complications

In terms of postoperative complications, Yukawa et al. [9] reported 6 patients of ATPS fixation; 2 patients developed postoperative dysphagia, which might have resulted from the stimulation of the esophagus by the screw tail process. Wang et al. [34] performed ATPS fixation on 10 patients with LCS injuries. Except for 2 patients with postoperative dysphagia, no other complication occurred, and all of the patients obtained early bone fusion. Of the 9 patients who underwent the ATPS fixation reported by Aramomi et al. [38], only 1 patient had screw penetration through the pedicle, but no neurological or vascular injury occurred. Among 22 patients of ATPS fixation reported by Zhao et al. [21], 1 patient had postoperative hoarseness, 2 had postoperative dysphagia, and 4 had pedicle screw penetration through the pedicle, but no neurovascular complications. The postoperative complications of ATPS fixation in different clinical studies are summarized in Table 5.

At present, the main complications regarding ATPS fixation reported in the clinical setting are postoperative esophageal irritation symptoms; no serious adverse consequences occurred. However, this does not mean that ATPS fixation is completely safe and has no serious complications; great importance should still be attached to intraoperative nerve, spinal cord, and vascular injuries and postoperative esophageal fistula [40,41].

Accuracy evaluation of screws insertion

The accuracy of screws insertion is a vital aspect of ATPS fixation; it is vital to effectively evaluate the accuracy of screws insertion. In view of the extensive clinical applications of cervical posterior pedicle screws fixation, many scholars [42–45] found that most of the screws that apparently penetrated the pedicle cortex did not cause the complications as expected, which may be because the pedicle has a certain safe space with the adjacent blood vessels and nerves. Wang et al. [6] also found in an anatomical experiment that cerebrospinal fluid, dural sac, and epidural fat existed around the spinal cord, which could play a certain buffering role. Moreover, the medial cortex of pedicle is significantly thicker than the lateral side, and the risk of injury during the screw insertion is relatively low [45–47]. However, due to the bony limitation of the transverse foramen, the vertebral artery is equipped with a poor escape ability and a high probability of injury when the screw penetrates the transverse foramen [48].

There is no unified evaluation standard for the accuracy of ATPS fixation currently. However, it has been clearly regarded as a critical injury when the following criteria are established, which might result in a substantial threat to blood vessels and nerves. When the screw penetrates through the pedicle:

1) the range of screw located outside the pedicle cortex is 50% greater than the screw diameter; 2) the external length of screw protruding out of the pedicle is greater than 4 mm; and 3) the outward part of screw penetrating outside occupies more than 25% of the transverse foramen.

Conclusions

The ATPS fixation is a valuable discovery in the field of LCS reconstruction in recent years, and it has the advantages of both anterior and posterior approaches. With the development of distinctive instruments, the clinical applications of ATPS fixation have been widely improved and promoted. Despite the apparent advantages of ATPS fixation, it is also necessary for us to clearly recognize the deficiencies, such as the high risk of screw insertion, and the lack of large sample size studies and long-term follow-up. Nevertheless, it is believed that with the maturity of digital devices and the development of precision medicine, ATPS fixation has a promising prospect.

Conflict of interests

None.

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