A novel method to evaluate transverse pedicle angle of lower lumbar using digital radiography

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Article

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Abstract

To investigate a novel approach of establishment for transverse pedicle angle (TPA) of lower lumbar spine using preoperative digital radiography(DR). CT dataset of the lower lumbar were reconstructed using MIMICS 17.0 software, then imported into the 3matic software for surgical simulation and anatomical parameters measurement. Mathematical algorithm of TPA based on Pythagorean theorem was established, all obtained data was analysised by SPSS software. CT dataset from 66 samples were reconstructed as digital model of lower lumbar vertebrate(L3-L5), AP length / estimated lateral length for L3 between right and left were significant statistically($P = 0.015$, $P = 0.005$). AP length of right for L4 was smaller than that of left after Paired *t*-test was executed($P = 0.006$). Both width of pedicle and length of pedicle (P2C1) are consistent with TPA(L3 < L4 < L5). No statistical differences in TAN-TPA and DR-TPA compared with real TPA. ICC for real TPA and DR-TPA within L3 is good reliability, ICC for real TPA and DR-TPA within both L4 and L5 are moderate reliability. Our novel approach can be well considered as a reliable way to determine the transverse pedicle angle from routine DR, width and length of pedicle within lumbar DR should be considered to determine the length and trajectory of screw during preoperation planning.

Introduction

Pedicle screw fixation technology is the standard method for maintain stability of spine during treatment of degenerative lumbar instability, spine tuberculosis[1], fractrue, septic spondylitis. Pedicle screw can supply stability for three-column of vertebrae through cortical bone of pedicle [2].

Freehand pedicle screw fixation during the operation is a universal and acceptable approach;[3–5] but despite that, a postoperative computed tomography (CT) study demonstrated that 3.9% of screw breach for free-hand pedicle screw technology was identified[6]. Another similar publication demonstrated 13.5% of misplace screw[5].

Even through herringbone based on relatively constant anatomical landmarks was mostly used to ensure the entry angle of pedicle screw; Indeed, TPA refer to herringbone is obviously less than the true TPA [7], that lead to entry point is closed to facet joint and posterior midline, to damage the stability of spine, even add the possible of inner wall rupture and nerve damage.

Some new approach comes out, such as computer navigation and robotic assistance improve the precision of pedicle screw implant[8]. Conversely, some researches reported that the accuracy of pedicle screw insertion between freehand technology combined fluoroscopy and intraoperative CT navigation is similar[9–11]; Similarlly, navigation and robotic assistance increase operation time and cost[12, 13], CT navigation and robotic assistance at present is controversial, and hard to popular application.

The deformation of pedicle belong to the lumbar vertebra varies greatly. It is very important for preoperative planning to reduce the risk of neurological deficits and lower extremity weaknesses. Digital

radiography (DR) is routinely radiological methods before internal fixation for lumbar surgery. The method of simulating surgery based on three-dimensional reconstruction can be used to obtain more accurate anatomical information[14].

To the best of our current knowledge, the size of TPA predicted from the standard DR has not published. In this study, an digital model of the vertebral body was established using CT data from human subjects, the simulated operation of pedicle screw insertion was compared with the simulated DR, it's an attempt to find a convenient and accurate method for evaluating the TPA using DR technology .

Methods And Materials

Specimen acquisition and Computer assisted-software

SOMATOM Definition Flash dual-source CT machine (Siemens Healthineers, Forchheim, Germany) was selected to scan the lumbar vertebral body of subjects, including L3-L4-L5 body. Parameters were set as: 120 KV, 205.50 mAs, layer thickness: 1 mm, all DICOM images (521px×512px) in 336 layers for each subject; All methods were performed in accordance with the relevant guidelines and regulations[15]. CT data was imported into Materialise's Interactive Medical Image Control System (MIMICS) 17.0 software (Materialise, Leuven, Belgium), the region of interest (ROI) were extracted using both "Thresholding" and "region growing" module. All 3D models of lumbar were automatically produced by "calulate 3D from mask" functional block, and then was imported into the 3matic software for surgical simulation and anatomical parameters measurement. The screw was designed using SolidWorks 2012 X 64 edition(Dassault Systems SolidWorksCorp., Waltham MA). The computer workstation: Lenovo thinkpad, Windows 7-64 bit operating system, processor Intel (R) Core(TM) i7-4600, running memory 8GB, 256 SSD hard disk.

The CT data of lumbar from subjects was collected in the outpatient and inpatient departments of Shaanxi Provincial People's Hospital. The inclusion criteria: Patients without/ with history of trauma but without fracture or dislocation from lower lumbar spine. The exclusion criteria are: (i) the vertebral body of patient have suffered from fracture, (ii) the patient has congenital or acquired skeletal deformity; (iii) patients with destruction of vertebral bone caused by tumor or infection (spinal tuberculosis).

Calibration of coordinate system

Object coordinate system(OCS) of veterbral was format to the World coordinate system(WCS), to keep each vertebral body has the same three dimension position in software. Origin point (0,0,0)was defined as the centerpoint of each vertebrate (except attachment) in World coordinate system(WCS), XY plane (axial plane) YZ plane (sagittal plane) ZX plane (coronal plane) was generated separately(**see Fig1a**).

Simulating DR of standard vertebral body

Mark function of 3-matic was used to separate the vertebral body and lumbar pedicle, to caculate the center of gravity of separated vertebral body, then both center point and vertebral body was aligned with Origin point. On the top view, the upper surface of vertebral body was aligned to XY plane, then translate and rotate function were executed repeatedly to normalize the vertebral body, all according to guideline of standardized lumbar DR[16](**see Fig. 1B and 1C**).

Standardized lumbar DR

Antero-posterior view(AP): pedicles and transverse processes on both sides display symmetrically, all the edges of the vertebral body show overlap well, but no double layered wall; Lateral view: all the edges of the vertebral body show overlap well, but no double layered wall(**see Fig.1B and 1C**).

Center point of pedicle

On the back view, parallel to XY plane, plane1 was produced when through the bottom of superior wall of pedicle; In the same approach, plane2 was created through the top of inferior wall of pedicle; Mid plane 1 was produced based on plane1 and plane2, In the same approach, parallel to YZ plane, plane3 and plane4 were generated based on inner wall and outer wall of pedicle, mid plane 2 between plane3 and plane4 was produced. Line 1(L1) was created by midplane1 and midplane2(**see Fig.1D**). Projection point onto vertebrate was created as point 1(P1), then P1 was aligned with articular process border shadow; A new plane 5 parallel to XZ plane was created through the top of inferior vertebral notches, center point(C1) of pedicle is the point which P1 was projected to the plane 5(**see Fig. 2A**).

Line 2(L2) was created by plane 4 and midplane 1, which is projected to vertebrate, the projection point(P2) is the entry point of pedicle screw placement. Plane 6 was created through C1 point and parallel to YZ plane, Point 3(P3) was set as P2 project onto plane 6 (**see Fig. 2B**). Under left view, P3 point was duplicated and meanwhile translated to heaviest color area of transverse process (P4) (**see Fig. 2C**).

Measurement approach

A sketch was created on the XY plane in 3matic, the five point (C1/P1/P2/P3/P4)was projected onto this sketch, new five point were created correspondingly(**see Fig. 2D**), distance between two points was measured.

Algorithm of TPA

According to the definition of TPA published previously[17], assessment method can be expressed as following: Under the standard AP view, the width of pedicle is marked as 2b, and the length of pedicle under lateral view is marked as L2, L2=a2+a3 then, the estimated formula of TPA is expressed as $\alpha \approx ATAN(b/L2)$. Measurement diagram in lumbar model and DR were revealed in **Fig.3.**

However, how to determine the length of the pedicle under the lateral view? We developed the formula as following: $L2 \approx a3 + \frac{1}{2}(a1+a2)$ (**see Fig.4**)

TAN-TPA was expressed as α=DEGREES(ATAN(b/(a2+a3))

DR-TPA was expressed as **β=DEGREES(ATAN(b/L2))**

TPA (γ) was measured using 3matic software.

Statistical analysis

All measurements of vertebral body in this study included left and right, and each vertebral body was measured by the same orthopaedic surgeon. All data was collected and putted into Microsoft Excel 2016, SPSS17.0 statistical software package (SPSS Statistics for Windows, Version 17.0. Chicago: SPSS Inc.) was employed to determine the statistical results. If the data is normal distribution and the equal variance, independent sample t-test was used to identity the difference of two groups, the paired *t* test is used for analyzing the difference between left and right of pedicles, and the results are expressed as the mean ± standard error (ˉx±SEM). The difference among multiple samples was tested by the LSD multiple comparison method; if the three groups of data were not normal or the variance was unequal, the Kruskal-Wallis H nonparametric test was used. Intraclass correlation coefficient (ICC)was used to test the consistency, all statistical tests were two-sided, and $P<0.05$ was considered statistically significant.

Results

Baseline information for CT data

According to the inclusion criteria, 66 samples were collected including male 29, female 37, the average age: 32.48±7.26(16-57years), all the result of measurement by 3matic software were displayed from **table 1** to **table 3**.

L3	N	Left				Right			
		mean	SD	min	max	mean	SD	min	max
Lateral length(mm)	66	17.11	2.27	12	22	16.81	2.44	11.23	22.55
AP length(mm)	66	4.8	0.72	3	8	4.69	0.68	2.50	6.41
a1(mm)	66	2.62	2.11	0.01	9.07	2.48	2.03	0.01	10.10
a2(mm)	66	4.51	1.76	1.36	8.17	4.26	2.03	0.80	8.29
a3(mm)	66	12.67	1.44	8.88	15.95	12.59	1.33	9.08	15.37
Estimated Lateral length(mm)	66	16.23	1.78	11.46	20.02	15.76	1.82	11.68	19.95
∠α (TAN-TPA)	66	15.99	3.24	9.39	25.75	15.97	3.51	7.15	28.19
∠γ (TPA)	66	15.99	3.24	9.38	25.76	16.43	4.81	7.15	42.70
∠β (DR-TPA)	66	16.61	2.63	11.16	24.67	16.50	2.54	8.67	22.93

Table 1. Baseline data of measurement for L3 vertebral body.

L4	N	Left				Right			
		mean	SD	min	max	mean	SD	min	max
Lateral length(mm)	66	17.62	3.77	10.05	25.10	17.72	3.66	11.56	27.42
AP length(mm)	66	5.58	0.84	3.82	8.69	5.43	0.77	3.84	7.14
a1(mm)	66	3.80	3.42	0.01	14.68	3.46	3.57	0.01	12.60
a2(mm)	66	6.08	3.38	0.52	14.68	6.43	3.58	0.75	14.84
a3(mm)	66	11.48	1.78	7.97	16.95	11.26	1.53	7.79	15.15
Estimated Lateral length(mm)	66	16.42	2.13	10.93	21.91	16.21	1.84	11.77	19.15
∠α (TAN-TPA)	66	18.35	5.23	10.85	32.11	17.70	4.56	10.60	29.57
∠γ (TPA)	66	18.35	5.22	10.84	32.12	17.70	4.55	10.60	29.58
∠β (DR-TPA)	66	18.93	2.95	12.44	25.96	18.66	2.98	13.34	27.54

Table 2. Baseline data of measurement for L4 vertebral body.

L5	N	Left				Right			
		mean	SD	min	max	mean	SD	min	max
Lateral length(mm)	66	18.17	3.32	12.02	24.58	18.05	4.27	8.61	26.53
AP length(mm)	66	6.64	0.93	4.66	8.84	6.56	1.03	4.57	9.49
a1(mm)	66	3.37	3.24	0.01	13.48	3.80	3.67	0.01	12.47
a2(mm)	66	5.65	3.22	0.51	12.32	5.83	3.35	0.21	12.50
a3(mm)	66	12.53	3.01	5.32	20.93	12.29	3.12	3.96	18.64
Estimated Lateral length(mm)	66	17.02	2.68	10.14	22.90	17.01	2.86	9.61	23.03
∠α (TAN-TPA)	66	20.56	4.22	13.17	29.50	20.92	5.82	13.09	35.32
∠γ (TPA)	66	20.56	4.21	13.17	29.47	20.89	5.81	13.10	35.31
∠β (DR-TPA)	66	21.52	2.94	16.26	28.43	21.38	3.55	14.20	32.42

Table 3. Baseline data of measurement for L5 vertebral body.

Testing of Standardized method for simulated digital radiology

Paired *t*-test was employed, the result for L3 shows that AP length / estimated lateral length between right and left were significant statistically(*P*=0.015, *P*=0.005). All other variables no significance. For L4 AP length of right was smaller than that of left after Paired *t*-test was executed(*P*=0.006). For L5, all observed variables between let and right has no difference. These result suggest that the simulation method to standard lumbar spine radiograph is feasible and reliable in this study. (**see Table 4**)

Moreover, width of pedicle (AP length) for of lower lumbar vertebra shows anatomical features: L3<L4<L5, and width of pedicle from subjects in our study is similar to that of CT data obtained from Indian population[18], length of pedicle (P2C1=): L3<L4<L5, which consistent with analytical feature of TPA (L3<L4<L5).

	L3		L4		L5	
	right	left	right	left	right	left
Lateral length(mm)	16.81±2.44	17.11±2.27	17.72±3.66	17.62±3.77	18.05±4.27	18.17±3.32
AP length(mm)	4.69±0.68	4.80±0.72*	5.43±0.77	5.58±0.84*	6.56±1.03	6.64±0.93
a1(mm)	2.48±2.03	2.62±2.11	3.46±3.57	3.80±3.41	3.46±3.57	3.37±3.24
a2(mm)	4.25±2.03	4.51±1.76	6.43±3.58	6.07±3.38	5.83±3.35	5.65±3.22
a3(mm)	12.59±1.33	12.67±1.44	11.26±1.53	11.48±1.78	12.29±3.12	12.53±3.01
Estimated Lateral length(mm)	15.76±1.82	16.23±1.78*	16.21±1.84	16.42±2.13	17.01±2.86	17.03±2.68
∠α (TAN-TPA)	15.97±3.52	15.99±3.24	17.70±4.56	18.35±5.23	20.92±5.82	20.56±4.22
∠γ (TPA)	16.43±4.81	15.99±3.24	17.70±4.56	18.35±5.22	20.89±5.81	20.56±4.21
∠β (DR-TPA)	16.49±2.54	16.61±2.63	18.66±2.98	18.93±2.95	21.38±3.55	21.52±2.94

Table 4. Differences between right and left for each measurement parameters. *means significant difference in left compared with right for each vertebrate.

Reliability of TPA by TAN method

The average of measured TPA nearly equal to this of TAN method, the difference between them is not significant statistically. These indicate the TAN method is very reliable way to calculate the TPA(**see Table 5**).

	L3-R	L3-L	L4-R	L4-L	L5-R	L5-L
∠γ (TPA)	15.97±3.51	15.99±3.24	17.70±4.56	18.35±5.22	20.92±5.82	20.56±4.22
∠α (TAN-TPA)	16.43±4.81	15.99±3.24	17.70±4.55	18.35±5.22	20.89±5.81	20.55±4.21
t	-0.622	0.002	-0.003	0.000	0.031	0.002
P	0.535	0.998	0.997	1.000	0.975	0.999

Table 5. Reliability analysis of TPA using independent t test. *means significant difference in TAN method TPA compared with real TPA.

Reliability of DR-TPA by measurement

Independent samples t test was used to distinguish the difference between TPA and DR-TPA, the result shows that difference between TPA and DR-TPA for L3, L4 and L5 is not significant respectively**(see Table 6**). All results show DR-TPA could be as a good method to instead the real pedicle TPA before the operation .

In addition, good location and angle of simulated screw fixation by our method was displayed in **Fig 5**. The real pedicle screw tunnel does not affect the anatomy of the zygapophyseal joint, and the spinal stability was not damaged by iatrogenic factors.

	L3-R	L3-L	L4-R	L4-L	L5-R	L5-L
∠γ (TPA)	15.97±3.51	15.99±3.24	17.70±4.56	18.35±5.23	20.92±5.82	20.56±4.22
∠β (DR-TPA)	16.49±2.54	16.62±2.63	18.66±2.98	18.93±2.95	21.38±3.55	21.52±2.94
t	–0.975	-1.220	-1.443	-0.778	-0.548	-1.522
P	0.331	0.225	0.151	0.438	0.585	0.130

Table 6. Reliability analysis of DR-TPA using independent t test. *means significant difference in DR-TPA compared with TPA.

Agreement analysis between TPA and DR-TPA

Intraclass correlation coefficient (ICC) was used to estmated the agreement between TPA and DR-TPA, that is to say, ICC was calculated the reliability of method for DR-TPA; According to the published guideline[19], ICC of L3-R [0.815 (95%CI: 0.715-0.883)] and L3-L [0.862 (95%CI: 0.784-0.913)] is good reliability; moderate reliability include: L4-R: 0.637 (95%CI: 0.469-0.761), L4-L: 0.622 (95%CI: 0.449-0.750), L5-R: 0.670 (95%CI: 0.512-0.784), L5-L: 0.577(95%CI: 0.391-0.718).

Discussion

Spinal fixation through pedicle screw is a classical procedure, in order to enhance stability used by spine surgeons, DR is routine examination which is helpful for precisely intraoperative positioning. In this study, we attempt to dig the useful data from DR for determining the TPA of lower lumbar during preoperation planing.

In recent years, some initial studies about accurate medicine attract people's attention, many technology were used to improve the accuracy of pedicle screw insertion, such as computer-based navigation and robotic-assisted guidance systems [20–24], pedicle screw entry point[25–27], TPA of lumbar[17, 18, 28], both scan-and-plan registration and CT-to-fluoroscopy registration methods is similar fluoroscopy time exposure[29]. Still, recent reviews demonstrate that these instrument are no better than freehand technologies, but also substantially increase the costs and operation time [12, 30, 31]. Overall, freehand

technology under monitoring with DR is still foremost procedure for almost spinal surgeons. In this study, little difference was identified between true TPA and DR-TPA, result of ICC for DR-TPA is available. AP length / estimated lateral length for L3 between right and left were significant statistically. AP length of right for L4 was smaller than that of left. These positive results could be caused by developmental differences. This method is simple, practical, feasible, and has good clinical application value. It is worth to promoting for all spinal surgeons.

According to relevant reports[32], morphology of pedicle varies in the process of growing. Many studies about morphological features of lumbar pedicle have showed some difference. The average pedicle width of normal Israel population(L3:8-9.7mm;L4:9.8-11.5mm;L5:14.5-16mm) from a cross-sectional retrospective study is smaller than those in degenerative lumbar spinal stenosis (DLSS) population[33]. Transverse pedicle isthmus width from CT data of Indian population (L3:8.4 ± 1.06mm; L4: 10.1 ± 1.18mm; L5:13 ± 1.48mm) was smaller than those in western population [18]. Pedicle width of lower lumbar in our manuscript is similar with the result from Indian population. That could be explained using the population characteristics(body mass index / ethnicity). This can be a predictor variable for determining the diameter of the pedicle screw during the fixation operation. Also, pedicle length is helpful for estimating the length of screw.

Our calculation formula of TPA is simple, related parameter is easy to obtain from DR of lumbar vertebrate. However, DR for lumbar should be standard or near to standard AP view, it is useful for predict or exclude the breaching the medial wall of lower lumbar pedicle[34]. According to research published[7], we also recommend that Weinstein method closest to the real screw canal is well used for implanting pedicle screws(**see** Fig. 5).

Conclusion

Our result demonstrate TPA of lower lumbar canbe calculated using standard DR before operation, estimated formula method show acceptable reliability, which easy to study for general spinal surgeons. Characteristic width of pedicle for lower lumbar is helpful for determining the diameter of screw, pedicle length is used for determining the length of screw. It's critical for safe insertion of pedicle screw.

Declarations

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Author contributions

S.X.W and X.L.D designed this research, S.X.W rebuilded 3D models and measured data, S.X.W also wrote the whole manuscript and revised it. X.L.D controled the research quality. S.Z.L and M.L selected the

subjects. M.G.H and Z.L collected the CT data. All authors reviewed this paper, and agreed to publish the final manuscript.

Data availability statement

The datasets used and/or analysed during the current study available from the first author and corresponding author on reasonable request.

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Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to X.L.D. The informed consent was obtained from all subjects. The study was approved by the Ethics Committee of Shaanxi Provincial People's Hospital.

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Figures

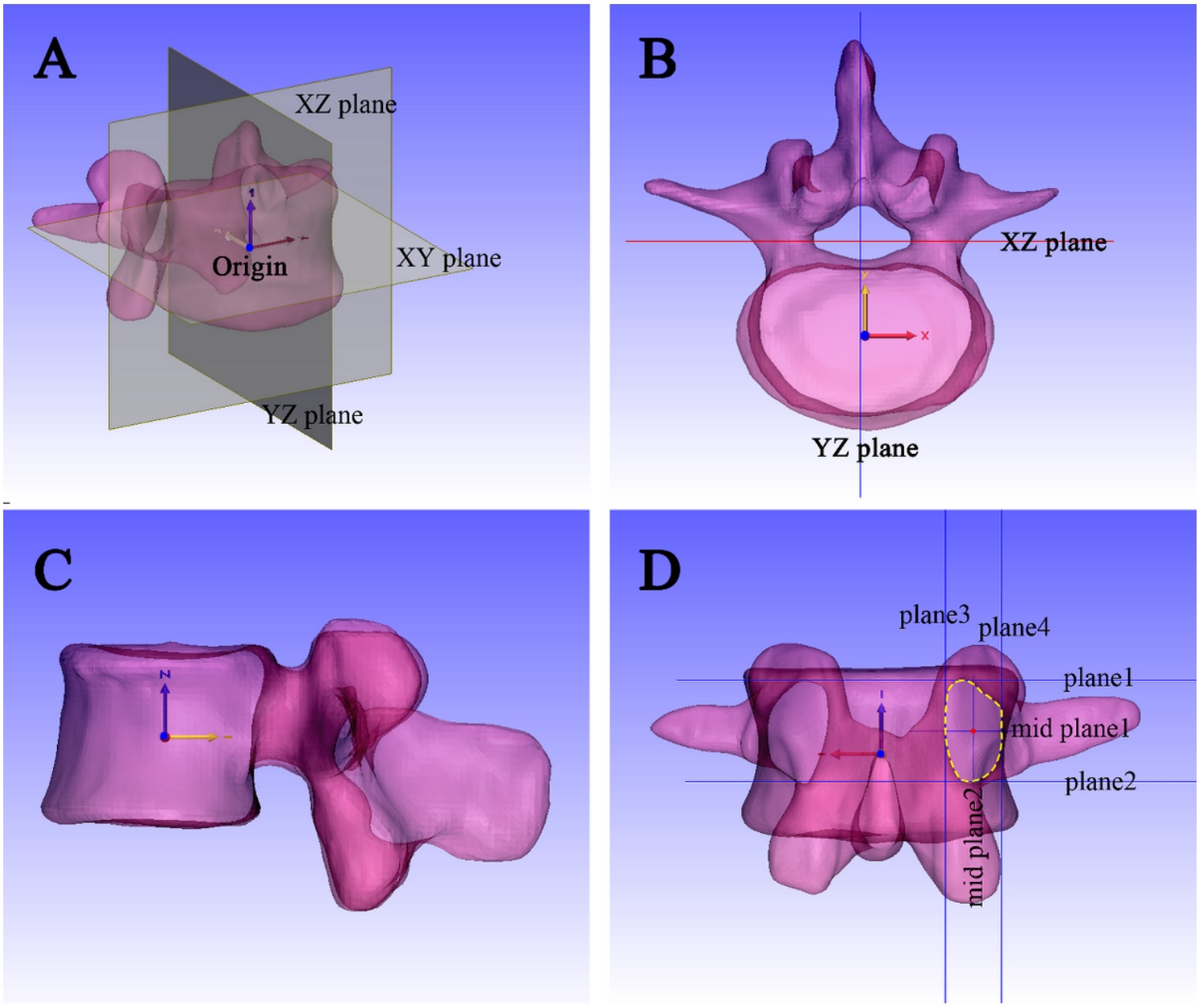

Figure 1

Establishment of standard coordinate system for lumar model. A. Establishment of XYplane, YZplane , XZplane; B. Top view of standard digital model; C. Right view of standard digital model; D. Center point of pedicle established by planes.

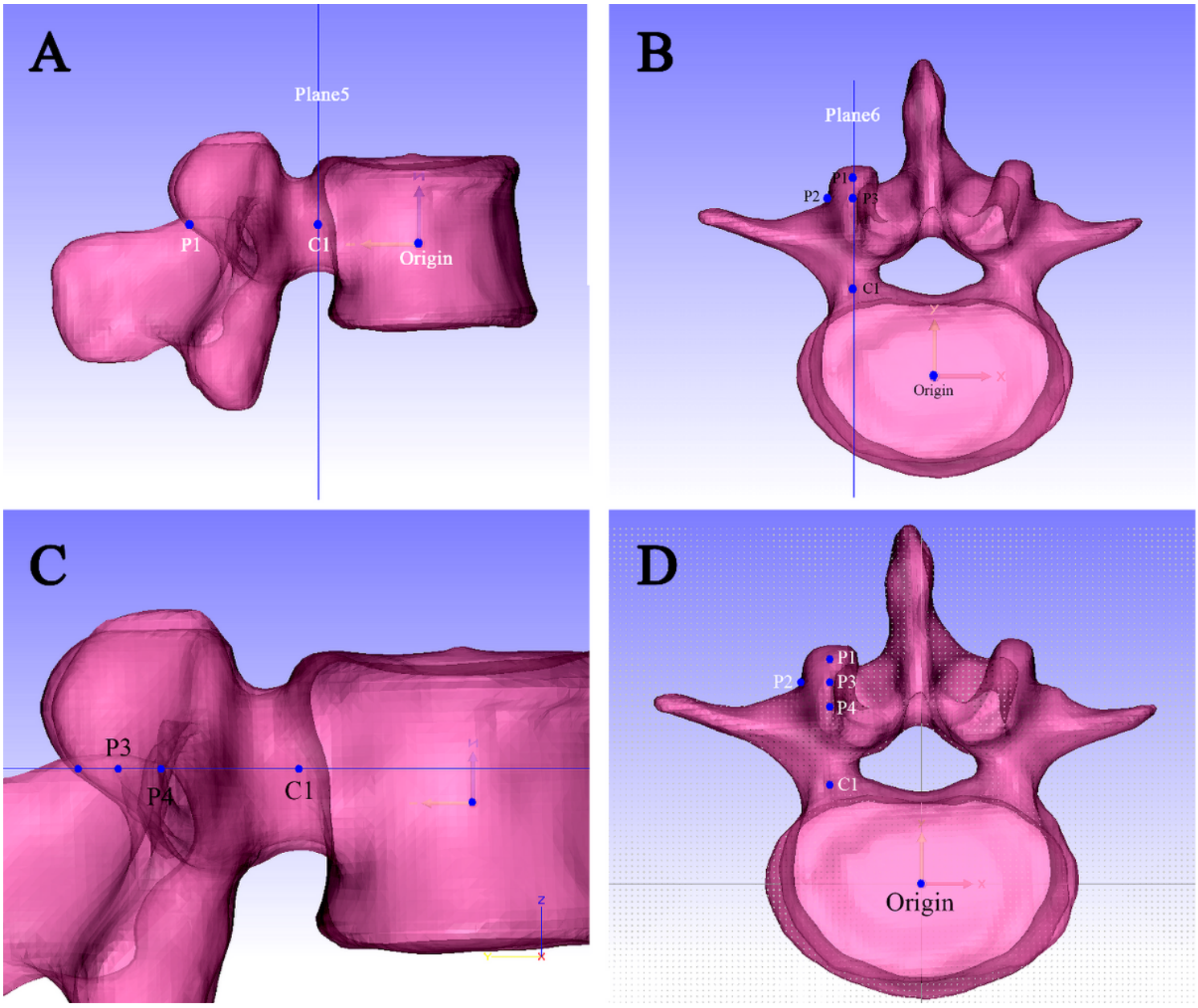

Figure 2

Establishment of five key points for this approach. A. determination for P1 and C1 point; B. determination of P2 and P3 point; C. P4 is located in the color heaviest area of transverse process; D. the five points were projected onto sketch.

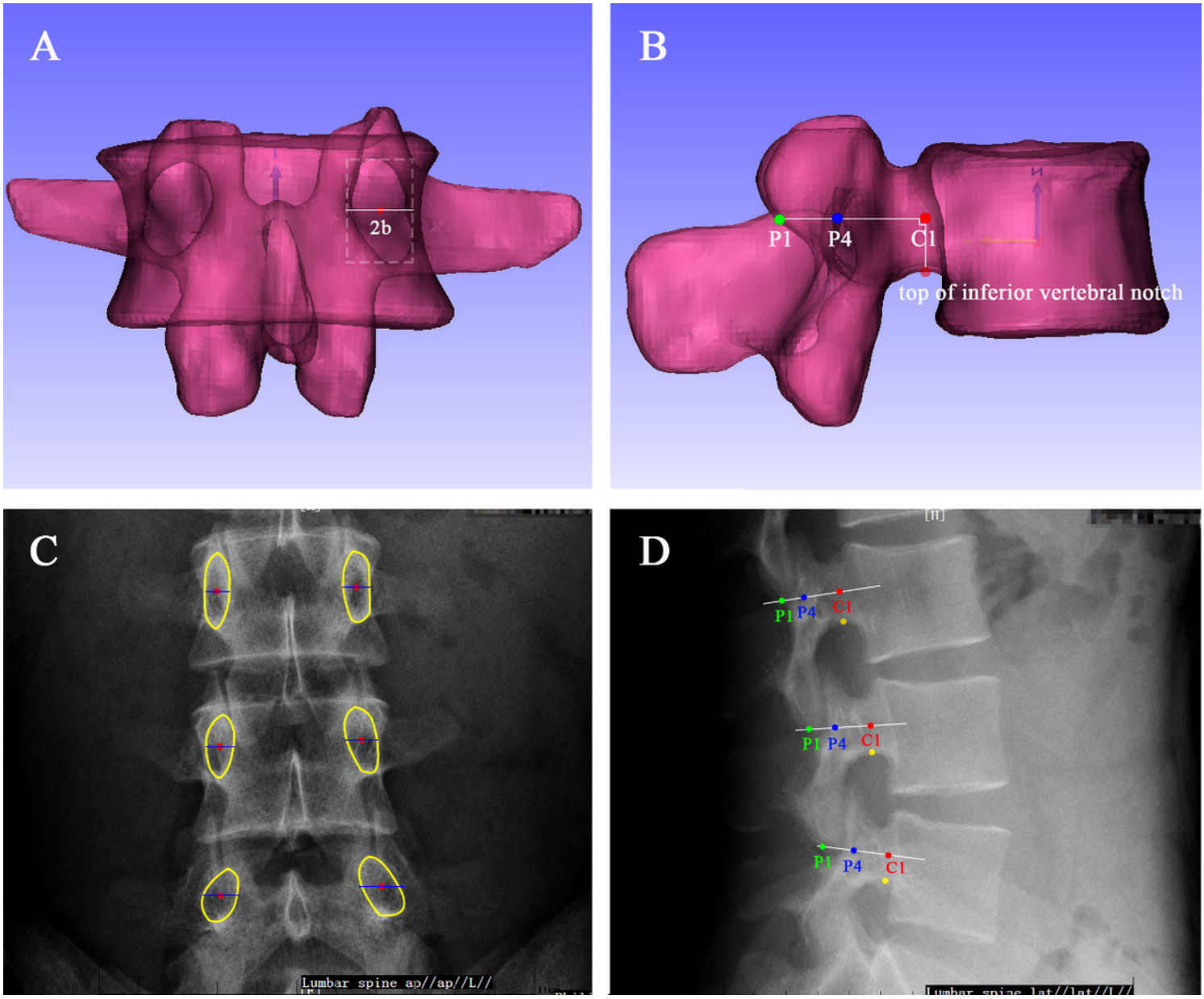

Figure 3

Measurement of TPA for lumbar model and DR. A. pedicle width of lumbar model under AP view; B. pedicle length of lumbar model under lateral view; C. pedicle width of DR under AP view; D. pedicle length of DR under lateral view, yellow means the top of inferior vertebral notch.

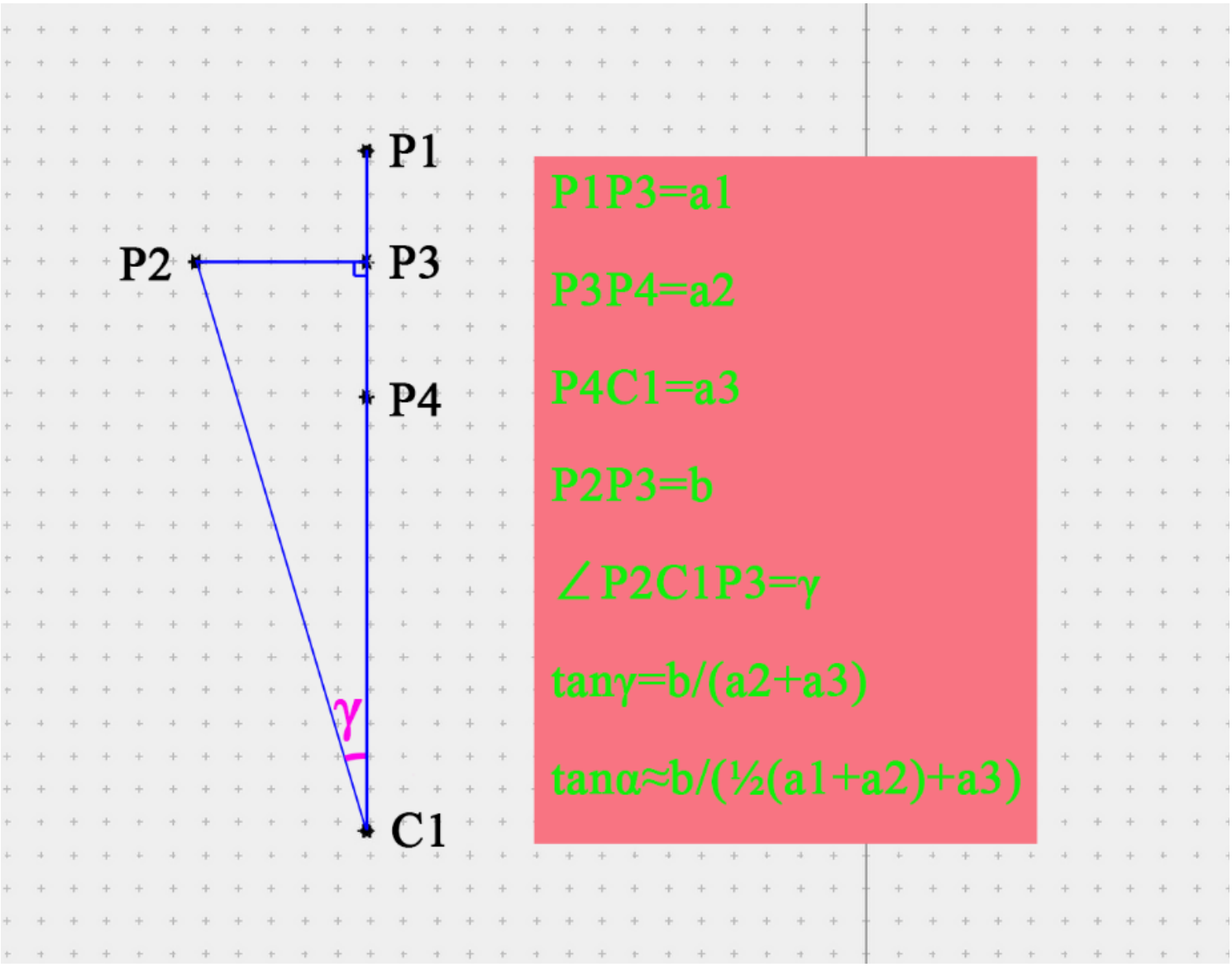

Figure 4

Schematic diagram of measurement length and TPA.

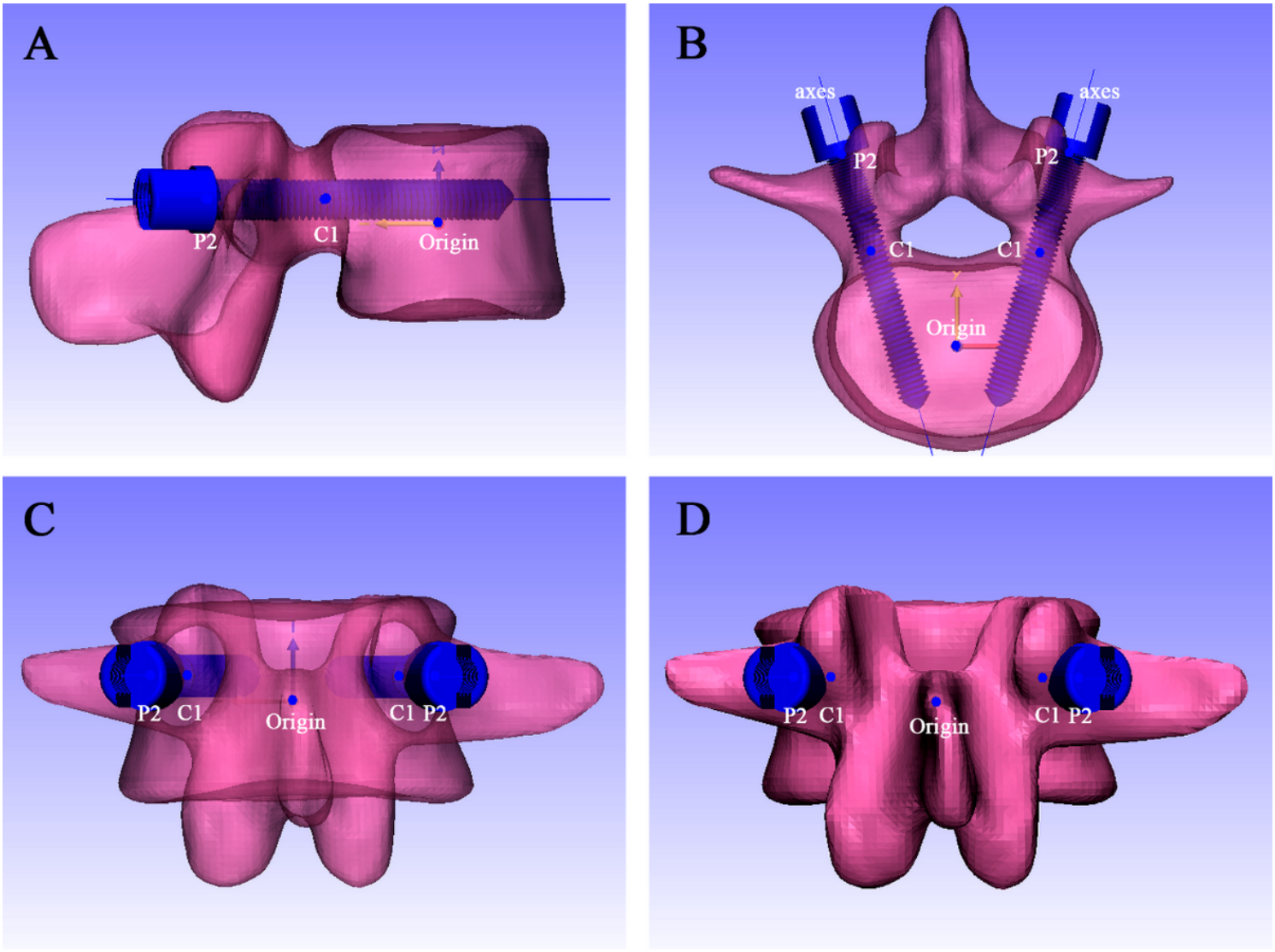

Figure 5

Simulate trajectory of screw placement by our approach in this manuscript.(screw size:φ6.5mm×4.5cm) (A, view left; B, view top; C, view back, transparency=0.5; D, view back, transparency=0)