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Research Article

Patient-specific three-dimensional printing spine model for surgical planning in AO spine type-C fracture posterior long-segment fixation

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ABSTRACT

Objective: The aim of this study was to compare duration of surgery, intraoperative fluoroscopy exposure, blood loss and the accuracy of pedicular screw placement between 3D model-assisted surgery and conventional surgery for AO spinal C-type injuries.

Methods: In this study 32 patients who were admitted with thoracolumbar AO spinal C-type injuries were included. These patients were divided randomly into two groups of 16 where one group was operated on using conventional surgery and the other group was operated on using 3D model-assisted surgery. During surgery, instrumentation time, amount of blood loss and intraoperative fluoroscopy exposure were recorded. Moreover, the status of the screws in the pedicles was assessed as described by Learch and Wiesner's and regional sagittal angles (RSA) were measured preop and postoperatively.

Results: It was found that there was a statistically significant difference in instrumentation time, blood loss and intraoperative fluoroscopy exposure in the 3D model-assisted surgery group (61.9 ± 4.7 min, 268.4 ± 42.7 ml, 16.3 ± 1.9 times) compared to the conventional surgery group (75.5 ± 11.0 min, 347.8 ± 52.2 mL, 19.7 ± 2.4 times) (t=4.5325, $P < 0.0001$ and t=4.7109, $P < 0.0001$ and t=4.4937, $P < 0.0001$, respectively) Although the screw misplacement rate of the conventional surgery group was higher than that of the 3D model-assisted surgery group, the only statistically significant difference was in the medial axial encroachment (t=5.101 $P=0.02$) . There was no severe misplacement of pedicle screws in either group. There were no statistically significant differences between postoperative RSA angles and were in both groups restored significantly.

Conclusion: The results of this study have shown us that the 3D model helps surgeons see patients' pathoanatomy and determine rod lengths, pedicle screw angles and lengths preoperatively and peroparatively, which in turn shortens operative time, reduces blood loss and fluoroscopy exposure.

Level of Evidence: Level I, Therapeutic Study

Introduction

The characteristics of AO spine type-C injuries are the impairment of all elements (bone structures plus the disco-ligamentous complex, which supports bony elements) from anterior to posterior, leading to displacement and gross instability. Accurate placement of pedicle screws in type-C fractures requires much effort to implant the pedicle screw in the optimal position. Severe instability can cause changes in orientation when opening with an awl or drilling a pedicle. Moreover, high-energy trauma can disrupt the detection of entry points. All these technically challenging attempts aim to achieve an accurate placement of the screws and to prevent serious complications related to pedicular screw misplacement like neurological, visceral, or vascular complications.[1]

Previously, spine fracture stabilization surgeries were commonly planned using two-dimensional (2D) radiographs. Due to the complex three-dimensional (3D) anatomical structure of the spine and the close relationship between the pedicle and important neurovascular structures, this method has been proven to be insufficient. Later on, computed tomography (CT) and magnetic resonance imaging (MRI) are being used widely to assess trauma patients in emergency departments. For suspected spine injury, 3D reconstructed CT images can be made without additional radiation exposure to help the diagnosis and treatment. Digital, patient-specific 3D models of the spine have been produced recently. As part of the preoperative plan, this can be incorporated into the generated report to prepare an inventory of planned surgical instrumentation.

The benefits of 3D print technology in spine surgery have been reported in the literature. It ensures the surgeon's visual perception with a realistic view, thereby increasing the convenience of the operation as a whole, and it is useful for communicating with patients and their relatives.[2-13] Most of the studies are related to the useful and relevant applications of 3D anatomical models in spinal deformity and tumor surgery. Although articles in this field contain studies of a small number of cases, the results of these studies confirm the latest evidence that 3D printing has a positive role in preoperative planning. However,

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there is a scarcity of literature to evaluate the advantages of the use of 3D printing technology in thoracolumbar spine fracture surgery. This study attempted to investigate the benefits of treatment of type-C thoracolumbar spine fractures with the aid of 3D models compared with conventional surgery. Moreover, it also investigated the effect of patient-specific 3D spine models on the perceptions of residents.

We think that 3D anatomical models provide the fourth dimension of tactile feedback to the surgeons, which can help them anticipate the technical challenges that may be encountered intra-operatively. Besides, we think that determining the pedicle screw sizes, the rod curvature, and length prior to the surgery, both through the premeasurements on the model and the simulation of the surgery on the 3D model, will increase the speed during the implantation of the construct. We hypothesized that performing the surgery with the 3D model would exhibit a shorter operation duration, less blood loss volume, less fluoroscopy number, and more accurate pedicular screw placement. This study attempted to investigate the benefits of treatment of type-C thoracolumbar spine fractures with the aid of 3D models compared with conventional surgery. Moreover, it also investigated the effect of patient-specific 3D spine models on the perceptions of residents.

Materials and Methods

Thirty-two patients, who were admitted to the emergency room with thoracolumbar AO spine type-C injuries, were eligible for this study. The criteria for inclusion and exclusion are listed in Table 1. We recorded the demographic and clinical characteristics of the patients including age, sex, level of injury, associated trauma, cause of injury, and Frankel classification. The level of injury in T1-T10, T11-L2, and L3-L5 was grouped as thoracic, thoracolumbar, and lumbar, respectively.

The study design

The study design of our study is the 2-group posttest-only randomized experimental. We used the simple randomized sampling technique for categorization in collecting the samples. To prevent sampling bias in the procedure, we performed patient with AO C-type spine injuries randomization sequentially, and patients were distributed into 2 groups: the conventional surgery group (control group) (16 cases) and the 3D model-assisted surgery group (experimental group) (16 cases). In the experimental group, the 3D model was used to assist the surgeries. The intraoperative parameters (instrumentation time, volume of blood loss, and intraoperative fluoroscopy number) and radiological evaluations (the status of screws in the pedicles and pre- and postoperative regional sagittal angles (RSAs)) were measured as the difference in the posttest scores between the 2 groups.

HIGHLIGHTS

- Preoperative 3D modeling has been shown to decrease fluoroscopy and instrumentation time as well as improve intraoperative speed while decreasing blood loss in spine surgery.
- This study aimed to investigate the benefits of treatment of type-C thoracolumbar spine fractures with the aid of 3D models compared with conventional surgery.
- The results showed a statistically significant difference in instrumentation time, blood loss, and intraoperative fluoroscopy time in the 3D model-assisted surgery group. The results from this study suggests that 3D model-assisted surgery could be helpful in preoperative planning and resident education.

Table 1. Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
• Patients admitted to our hospital with spinal trauma • Patient with complete CT image • AO Spine Type-C fractures	• Previous spine surgery • Congenital deformity of spine or vertebrae

CT, computed tomography.

Assessment of the parameters among groups

The intraoperative parameters (instrumentation time, volume of blood loss, and intraoperative fluoroscopy number) were recorded during the surgery. Pre- and postoperative CT images were obtained and evaluated with the program Sectra (Sectra AB, Linkoping, Sweden) by 3 orthopedic surgeons involved in the research. Computed tomographic images were evaluated in a blinded fashion. The distribution of the screws was noted. The status of screws in the pedicles was classified as described in the study by Learch et al[14] and Wiesner et al.[15] Evaluation of screw placement was performed according to the criteria including assessment of the coronal and sagittal CT images. In this classification, there are 4 main categories for screw misplacement: encroachment, if the pedicle cortex could not be visualized, minor penetration (frank penetration (FP) <3 mm) when the screw trajectory was <3 mm outside the pedicular boundaries, moderate penetration (FP 3-6 mm) when the screw trajectory was 3-6 mm outside the pedicular boundaries, and severe penetration (FP > 6 mm) when the screw trajectory was >6 mm outside the pedicular boundaries. We assessed RSAs before and after surgery. Regional sagittal angle shows the angle between the upper end plate of the vertebra above the fractured vertebra and the lower end plate of the vertebra below the fractured vertebra.

Three-dimensional printing solid models

All 3D models have been created in our university at the Department of Anatomy Digital Imaging and 3D Modeling Laboratory without any support from other centers (by F.G., M.A.O.). The proposed model was printed by Mass Portal Pharaoh XD 20 Formlabs 2 (Formlabs Inc., 35 Medford St. Suite 201, Somerville, MA, USA). The average time to print the model was around 4-6 hours, and no patient in the 3D model-assisted surgery group had to wait due to the time spent creating the models.

Surgery

All surgeries were performed (by the same experienced spine surgeon) when the general condition of the patients was suitable, all the radiological examinations were performed, and consultations were finished in the emergency department (<48 hours). All patients underwent a surgery for long-segment posterior instrumentation under general anesthesia where the posterior midline was approached, centering on the fractured vertebra according to the technique of Roy-Camille et al.[16,17] In the conventional surgery group, the pedicle screw sizes, the transverse connector sizes, and the rod length-bending were defined during the surgery, whereas in the 3D model-assisted surgery group, the pedicle sizes, the rod curvature, and length were already determined prior to the surgery, both through the premeasurements on the model and the simulation of the surgery on the 3D model (Figures 1A-C, 2F, F).

Simulation of the surgery on the three-dimensional model

First, the residents were informed by experienced spine surgeons (O.A. and A.M.O.) about the procedure of pedicle screw implantation. The simulation of the surgery was done in the operation room with a sterile implant and 3D model. For the sterilization of the model, we simply begin by prewashing the 3D model using hot

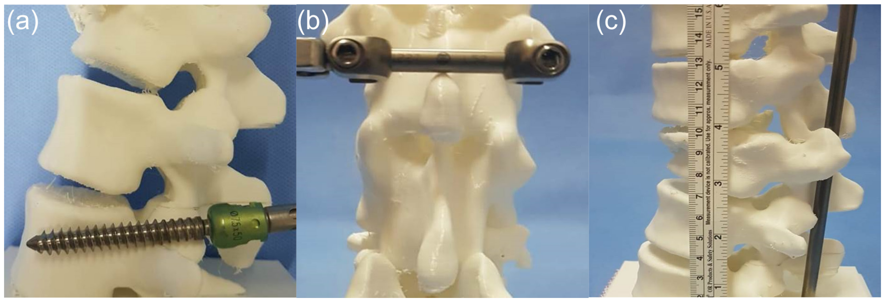

Figure 1. a-c. Preoperative determination of the pedicle screw size (a), transverse connector size (b), and rod length (c) on the three-dimensional (3D)-printed model by the 3D-assisted surgery group.

water and then applying soap on all reachable surfaces. After applying soap, we washed the 3D model again with warm water at least for 2 minutes and washed all the soap away. Then, we submerged the 3D model in isopropyl alcohol in a 70/30 ratio with water for about 5-10 minutes to ensure proper sterilization. Simulation of the surgery on the 3D model was done as described in Figure 2A-H. Subsequently, the position of the applied screws on the 3D model was assessed by fluoroscopy (Figure 3A-D). If necessary, the pedicle screw could be modified, and the ideal entry point and direction angle of the pedicle screw could be determined (Figure 4A,B). During the simulation of the surgery, the number of fluoroscopies were mostly 2, except that the pedicle screw needed to be modified and the ideal entry point and direction angle of the pedicle screw was determined. We think the number of fluoroscopies during the surgery directly affects some surgical outcomes like the operation time and bleeding amount. Moreover, fluoroscopy during the surgery different from simulation process directly affects the patient, surgery team, and anesthesia team. Because of all these, the number of fluoroscopies used during the simulation is not included in 3D model-assisted surgery group. Patient-specific 3D models are not only used to study the anatomy or to simulate the surgery preoperatively but they can also guide the appropriate choice of screw length-diameter together with the angle of approach (screw trajectory) while implanting pedicle screws during surgery. They are used to investigate fracture anatomy and provide practicing opportunities to trainees in their surgical skills prior to entering the operating theater. They also help in the choosing of the right size of screws with the appropriate angle of approach at the time of operation during implantation (Figure 5A-F). In the 3D model-assisted surgery group, virtual models of the inserted pedicle screws were used with the generated report to make the instrumentation inventory ready for operation. The time spent for the simulation of the surgery preoperatively on 3D model was not included in the 3D model-assisted surgery group.

Evaluation of the three-dimensional model's perception

The anatomical landmarks were measured on the original CT images, the STL image, and the CT images of the 3D model and compared. A

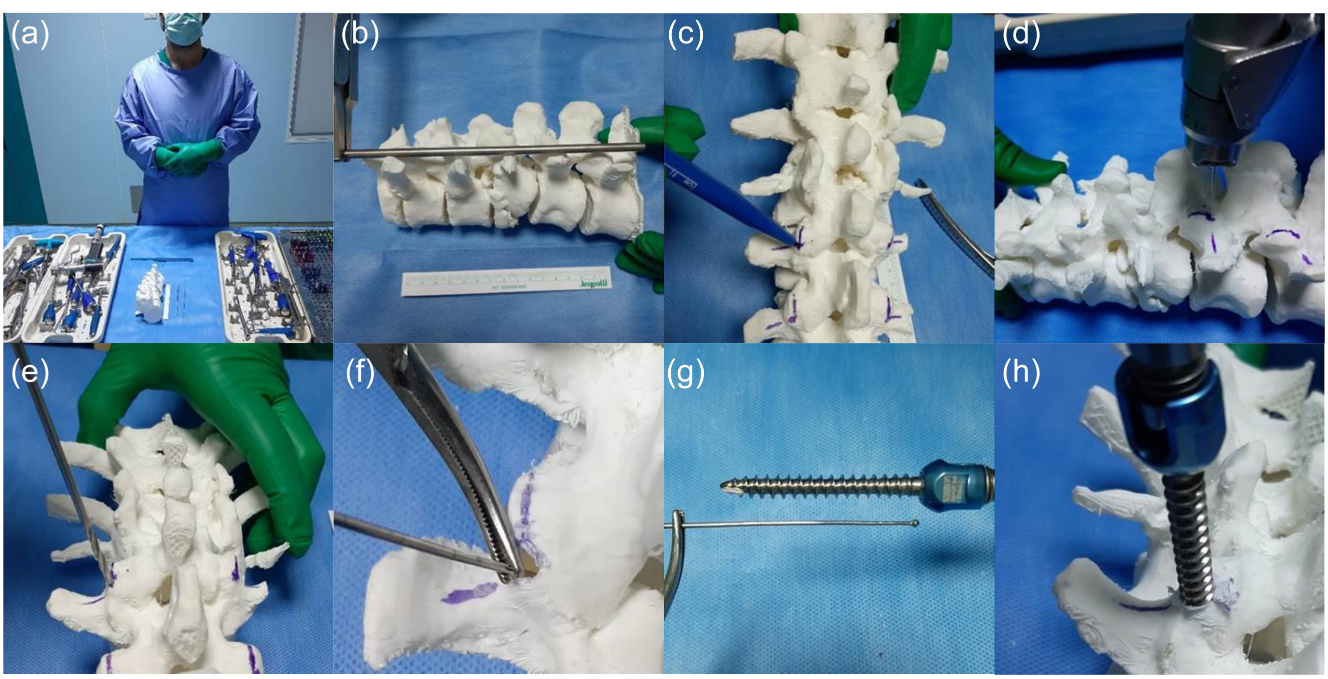

Figure 2. a-h. Simulation of the surgery on the three-dimensional model. Preparation of the table for surgery simulation (a). First, the rod length was determined on model (b). The entry point was located with a marker on the model (intersection of the lateral margin of the facet joint and the line passing through the longitudinal midline of the transverse process) (c). A K-wire was inserted to the entry point of the pedicle screw (d). With a guidewire, the optimal direction angle for the pedicle screw implantation was decided. Subsequently, drilling with a small-diameter drill into the vertebrae was performed to make a hole and the drilling was continued with tappers up to 5 mm (e). A small spherical tip probe was used to examine the opening of the pedicle screw entrance and to confirm the reliability of the pathway for the pedicle screw. Further, the length of the drill hole was also determined to decide the screw length (f). Pedicle screw size was determined (g). Finally, the pedicle screw was gently placed (h).

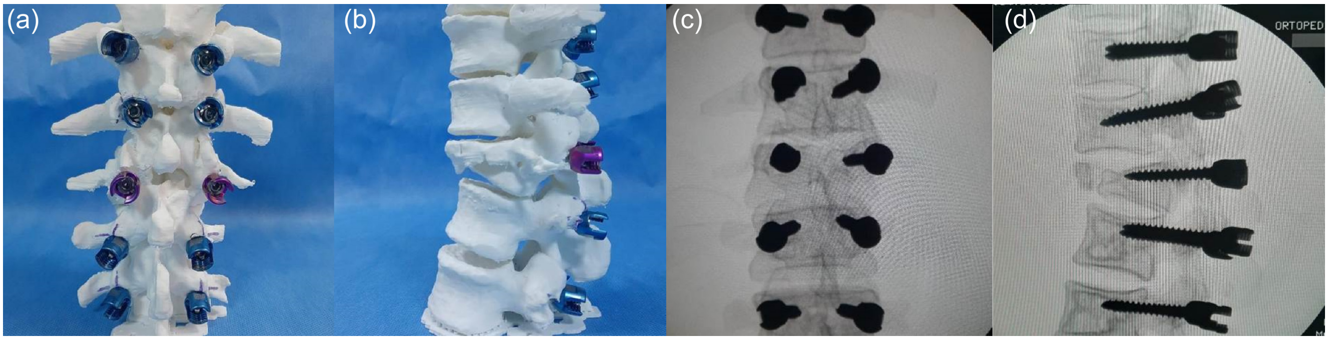

Figure 3. a-d. All pedicle screws were placed into the three-dimensional (3D) model (anteroposterior (a)–lateral (b) view). Assessment of the screws by fluoroscopy (anteroposterior (c)–lateral (d) view). The pedicle screw positions on the 3D model were with acceptable accuracy.

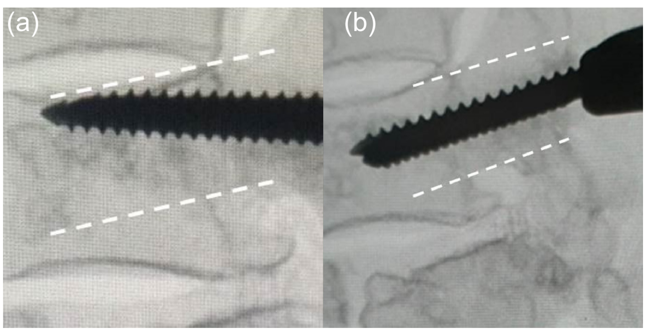

Figure 4. a, b. The position of the screws on the three-dimensional model is evaluated with fluoroscopy, and cranial misplacement of the pedicle screws was recognized in the sagittal view (a). With the revision of the position of the pedicle screws, the ideal entry point and direction angle for the pedicle screws were determined (b).

perfect correlation was achieved ($r=0.97$, $P < .001$). A questionnaire developed by the researchers was used to understand the effect of the 3D model on the perception of residents although none of them were involved in the study. The questionnaire consisted of 16 items, a numerical scoring scale from 1 to 10. Further, it contained an open-ended questions section concerning the 1 : 1 solid model. Resident doctors were asked to answer the questionnaire by examining the radiograph, the CT image, and the 3D model of the spinal fracture-dislocation case. The internal consistency coefficient was calculated for the reliability study of the questionnaire.

Statistical analysis

Data were analyzed using Student's *t* independent sample test, chi-square test, and Friedman test. $P < 0.05$ was considered statistically significant. Data are presented as mean ± standard deviation. Statistical analyses were performed using Statistical Package for the Social Sciences version 23.0 software (IBM SPSS Corp., Armonk, NY, USA).

The study was approved by the suitably constituted Ethical Committee at the Researches Department of our university, within which the work was undertaken, and the study conforms to the Declaration of Helsinki (18-12/6).

Results

When both groups were compared, there was no statistical difference with respect to age, gender, level of injury, associated trauma, cause of injury, and the Frankel classification (Table 2).

Independent measurements by all 3 physicians revealed full compliance when radiological evaluations for all patients were compared.

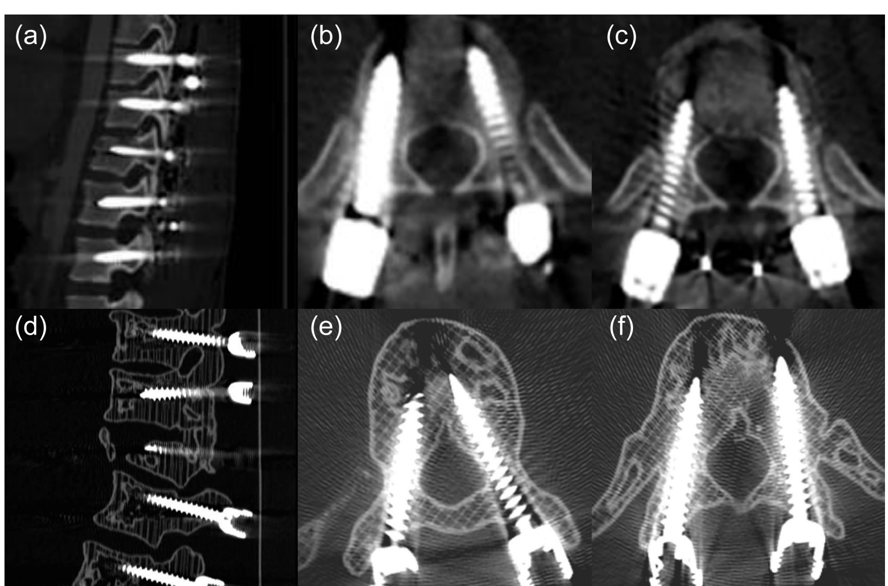

Figure 5. a-f. All pedicle screw sizes determined preoperatively on the three-dimensional (3D) model were used during surgery sagittal (a)–axial (b, c) view by computed tomography (CT) scan of the model with implanted pedicle screws and sagittal (d)–axial (e, f) view (same vertebral segments with axial CT scans of the 3D model of the patient's postoperative CT scan).

Table 2. Comparison of the 2 groups

		Conventional	3D Model-Assisted	*t* or χ^2	*P*
N		16	16		
Sex	Female	8	10	0.5079	0.4760
	Male	8	6		
Age (years)		38.8 ± 13.4	37.2 ± 13.8	−0.3247	0.3738
Level of injury	Thoracic (T1-T10)	3	4	0.6667	0.4142
	Thoracolumbar (T11-L2)	13	12		
	Lumbar (L3-L5)	-	-		
Injury	Fall	9	13	1.2243	0.2685
	Traffic accident	7	3		
Associated trauma	Head injury	3	2	1.0088	0.9085
	Pulmonary trauma	4	5		
	Extremity fracture	3	2		
	Pelvic fracture	2	3		
	Abdominal trauma	2	1		
Frankel classification	A	3	2	1.9857	0.5754
	B	5	3		
	C	6	6		
	D	2	5		
	E	-	-		

The level of injury in T1-T10, T11-L2, and L3-L5 was grouped as thoracic, thoracolumbar, and lumbar, respectively. No statistical differences were seen with respect to gender, age, level of injury, associated trauma, time to operation, and Frankel classification among the groups ($P > 0.05$).

Screw distributions are shown in Table 3. Although the screw misplacement rate of the conventional surgery group was much higher than that of the 3D model-assisted surgery group, the only statistically significant difference was in the medial axial encroachment ($t = 5.101$, $P = .02$) (Table 4). There was no severe misplacement in both groups. Moderate displacement was seen only in 3 patients in the conventional surgery group. Hence, with the exception of these 3 patients in this study, penetration <3 mm was thought to be in the safe zone because it neither affects the stability of the posterior instrumentation nor harms the neurovascular structures. In both groups, RSA was restored significantly postoperatively (Table 5).

There was a statistically significant difference in instrumentation time, blood loss, and intraoperative fluoroscopy numbers in the 3D model-assisted surgery group (61.9 ± 4.7 minutes, 268.4 ± 42.7 mL, 16.3 ± 1.9 times) compared to the conventional surgery group (75.5 ± 11.0 minutes, 347.8 ± 52.2 mL, 19.7 ± 2.4 times) ($t = 4.5325$, $P < 0.0001$ and $t = 4.7109$, $P < 0.0001$ and $t = 4.4937$, $P < 0.0001$, respectively) (Table 6).

Table 3. Pedicle screws placed in T1-T10, T11-L2, and L3-L5 were grouped as thoracic, thoracolumbar, and lumbar, respectively

		Conventional n = 162	3D Model-Assisted n = 160	χ^2	*P*
Distribution (n)	Thoracic	62	80	4.6707	0.0967
	Thoracolumbar	80	66		
	Lumbar	20	14		
Distribution of screws regarding the vertebrae level	T2	4	2		
	T3	4	2		
	T4	2	2		
	T5	8	8		
	T6	8	8		
	T7	2	8		
	T8	4	14		
	T9	10	16		
	T10	20	20		
	T11	20	24		
	T12	20	14		
	L1	20	14		
	L2	20	14		
	L3	14	10		
	L4	6	4		

No statistical differences were seen in screw distribution among the groups ($P > .05$).
3D, three-dimensional.

Table 4. Comparison of the screw misplacement in the 2 groups

		Conventional (n = 162)		3D Model-Assisted (n = 160)		χ^2	*P*
Screw misplacement		N	%	N	%		
Lateral axial	Encroachment	14	8.6	7	4.3	2.404	0.09
	FP < 3 mm	8	4.9	2	1.2	3.629	0.05
	FP 3-6 mm	3	1.8	-		2.991	0.13
	FP > 6 mm	-		-			
Medial axial	Encroachment	18	11.1	7	4.3	5.101	0.02
	FP < 3 mm	3	1.8	0		2.991	0.13
	FP 3-6 mm	-		-			
	FP > 6 mm	-		-			
Anterior axial	Encroachment	9	5.5	3	1.9	3.039	0.07
	FP < 3 mm	2	1.2	-		1.988	0.25
	FP 3-6 mm	-		-			
	FP > 6 mm	-		-			
Caudal sagittal	Encroachment	5	3.1	4	2.5	0.102	0.51
	FP < 3 mm	-		-			
	FP 3-6 mm	-		-			
	FP > 6 mm	-		-			
Cranial sagittal	Encroachment	8	4.9	3	1.9	2.289	0.11
	FP < 3 mm	-		-			
	FP 3-6 mm	-		-			
	FP > 6 mm	-		-			

Although the screw misplacement rate in the conventional surgery group was much higher than that in the 3D-assisted surgery group, the only statistically significant difference was in the medial axial encroachment ($t = 5.101$ $P = .02$). There was no severe misplacement in both groups. Moderate displacement was seen only with 3 patients in the conventional surgery group.
FP, frank penetration; 3D, three-dimensional.

Table 5. RSAs were restored significantly in all patients postoperatively

RSA	Conventional	3D Model-Assisted	*t*	*P*
n	16	16		
RSA Pre-op.	20.4 ± 9.0	18.4 ± 9.9	0.6024	0.5514
RSA Post-op.	2.5 ± 0.8	2.4 ± 0.6	0.0759	0.9400

No statistical differences were seen in the pre- and postoperative RSA of both groups.
3D, three-dimensional; RSA, regional sagittal angles.

Perception of the 3D model

In the present study, Cronbach's alpha coefficient, calculated for reliability, was found to be 0.87 based on which we can say that the survey is reliable. The residents who reviewed the models scored significantly higher in the quality of their surgical plan. Resident doctors had more positive perceptions stating that they found a 1 : 1 solid model to be useful. When x-ray, CT, and 3D models were compared, the results based on the answers of the questionnaire showed a significant increase in favor of the statistical analysis of the 3D fracture model. In terms of perception, fracture visualization, and intervention planning, CT and the 3D model can be seen in a statistically noteworthy level compared to the x-ray in items 1-16.

Some of the open-ended comments about the 3D model are "It enables a better understanding of the overall fracture, thus easing the orientation process," "It is easier to see the fracture and plan the treatment on a more realistic approach,"' and "Posterior instrumentation is easier throughout the surgery since one can get a very clear idea about the entry point, the rod length, the desired rod curvature, the transverse connector size, the screw size, the screw directions, and can even properly plan the screw in teratology preoperatively."

Discussion

When considering pedicle angles and attachment to the vertebral body, the complicated anatomy of the thoracic vertebrae carries various challenges than lumbar vertebrae to the freehand fixation technique of pedicle screw for accurate placement. The successful implantation process is still fundamentally a combination of experience and

Table 6. The comparison of surgical parameters of the 2 groups.

	Conventional	3D Model-Assisted	*t*	*P*
n	16	16		
Instrumentation time (minutes)	75.5 ± 11.0	61.9 ± 4.7	4.5325	< 0.0001
Blood loss (mL)	347.8 ± 52.2	268.4 ± 42.7	4.7109	< 0.0001
Fluoroscopy (n)	19.7 ± 2.4	16.3 ± 1.9	4.4937	< 0.0001

Instrumentation time, blood loss, and fluoroscopy number were statistically less in the 3D model-assisted surgery group compared to the conventional surgery group ($P < .0001$ for all).
3D, three-dimensional.

surgical skills of the surgeon and requires a steep learning curve.[18] The use of image guidance devices during the operation ensures that the surgeon can safely and reliably implant thoracic pedicle screws with decreasing fluoroscopy number.[19] Computed tomography-based navigation is mostly used by spine surgeons. However, the need for a steep learning curve, the requisite preoperative working-out (specific protocol of CT), the data collection and transmission, and patient registration have become problems.[20] The advancement of intraoperative navigation technology based on 2D and 3D navigation seems to be a probable solution to such problems.[21] Especially in the thoracic spine region, placement of pedicle screws is the main application requirement for 3D printing auxiliary screw implantation. Due to the changes of key anatomical landmarks and the influence of the tissues surrounding the target structures, it is troublesome to specify the entry point and trajectory of the pedicle screw during freehand pedicle screw placement.[3] The use of a 3D model for assisting surgery registration was not required. With the help of the 3D model, the surgeons can see patients' pathoanatomy and also select the instruments which are planned for posterior instrumentation at the beginning of the surgery for customized surgical planning. All these decrease fluoroscopy time and equally radiation dose during surgery. Moreover, the time needed for C-arm maneuvers for each segment to place the pedicle screw was decreased.

In the 3D model-assisted surgery group, the operation plan was made with the radiograms together with the 3D spine models where all the pedicle screw sizes, transverse connector sizes, and the rod lengths were determined preoperatively. The 3D printing technique is a novel technique for better sectioning of explants for pathology purposes. It permits a more accurate estimation of the patient's bone condition, especially in the fractured spine, and increases the level of understanding. Three-dimensional models are helpful for preoperative visualization and surgical planning, all of which can support the fact that 3D model-assisted surgery is better than conventional surgery in handling spinal fractures, by decreasing all of the intraoperative outcomes (operation time, volume of blood loss, and the number of intraoperative fluoroscopies). Although there are no studies on the use of 3D printing in thoracolumbar fracture surgery, in most studies among the few existing ones, these are related to the application of the 3D model in spine surgery (deformity and tumor), similar to our results, a number of advantages of the application of these models in spine surgery have been delineated, like reduced blood loss and surgery time, decreased radiation exposure, higher accuracy in screw placement, and ease of use and effectiveness in relation to its costs.[2-12,21-25] Moreover, it has the advantage of maintaining visual sense for the surgery team through a real appearance, thereby increasing the overall understanding of the planned surgery.[3] Three-dimensional models allow improved perception and are more beneficial in teaching pathological anatomy of the spine fracture site to surgeons not specialized in spine surgery. By understanding the individual fracture anatomy and anatomical bony landmarks, younger surgeons easily decide the path of screws to be implanted on the spine, desired level of correction, and the required reconstruction procedures. Guarino et al[26] in their prospective study on the benefits of 3D models in pediatric spine surgery stated that performing 3D model-assisted surgery could maintain substantial utility, especially in preoperative virtual planning, reduction in operative time, and surgical navigation. Izatt et al[27] pointed out in their report that in 11% of cases, certain anatomical details can only be detected on the 3D model, and in 65% of cases compared with CT or MRI, the anatomy was better visualized on the 3D model. In addition, 3D modeling affects the surgeon's choice of implant material in 52% of cases and the surgeon's decision about the implant position in 74% of cases. In most of the articles reviewed, some of the benefits of using 3D printing technology in spinal surgery are reduced blood loss, reduced radiation exposure during surgery, better explanation of the pathology and surgery to patients, and a better understanding of interventions by the surgical team to collaborate for an effective surgery.[4,7,9,10,12]

Three-dimensional printing technology can print an identical morphometric spine.[25] The 3D model of the upper cervical spine was used to investigate the advantages in the placement of the anterior occiput-to-axis screw. Among the benefits of assisting spine surgery with the 3D spine model are precise morphometry of the osseous spine, low cost, receiving readily existing data (CT or MRI) from hospital's radiology information system, accurate 1 : 1 solid 3D models from the patient's data (CT or MRI), preventing ethical issues around the use of human cadaveric specimens, absence of smell and hygienic providence of cadaver specimen, and special storage not required. The authors concluded that the models would be a better choice for studying the feasibility of intraosseous spinal fixation screw trajectory.[28]

In contrast to the lumbar spine, pedicle screw implantation needs attention in the thoracic spine due to the reduced size of the pedicle and the complexity of the anatomy. In conventional surgery, spine pedicle screw misplacement rates were reported to range from 3% to 55% for the thoracic spine and 5% to 41% for the lumbar spine.[29-31] When using standard fluoroscopic imaging, while placing the pedicle screw with standard fluoroscopy, even experienced surgeons during the surgery can mislead medially in 5% and inferolateral in 15% of the cases.[32] Medial pedicle penetration of pedicle screw >4 mm may damage neural structures resulting in neurological complications. The pedicle invasion of <2 mm is considered reliable and uncomplicated in the literature. However, there is no reliable evidence to prove this. Even so, most spine surgeons consider this amount of penetration as a safe zone.[33] Therefore, the significance of precise pedicle screw implantation implies that the screws are fully contained in the pedicle and no cortical invasion was found early. Most of the papers in the literature are related to the creation of patient-specific drill guides and templates for pedicle screw placement during spinal deformity surgery. Three-dimensional guides can be used as a method to improve pedicle screw correctness during the surgery by overcoming the low perception in patients with complicated anatomical landmarks or in key areas where screw misplacement may even cause major complications during surgery. However, the author points out that the process is time-consuming, and it is necessary to prepare in order to properly accommodate the template on the bone surface.[2,6,7,9,10] A 3D printing, patient-specific navigation template is not convenient in emergency surgeries because it takes a lot of time and preparation work may take up to 2 days, especially given that designing a template is time-consuming.[4] Manual segmentation and conversion into a stereolithography file format and printing of the model were done in our university hospital at the anatomy department by F.G. and M.A.O. (professor doctors at the anatomy department). All these did increase the speed, and in our study, the printing time for each model was about 4-6 hours. Therefore, no patient in the 3D model-assisted surgery group had to wait for surgery due to time spent creating the models. Although we did not use 3D print templates in this study, the screw misplacement rate in the conventional surgery group was much higher than that in the 3D model-assisted surgery group, but the only statistically significant difference was in the medial axial encroachment. There was no severe misplacement in both groups. Moderate displacement was seen in only 3 patients in the conventional surgery group. Unlike the conventional surgery group, in our study, simulating the surgery preoperatively in order to guide the appropriate choice of screw length-diameter along with the angle of approach (screw trajectory) while implanting pedicle screws during surgery contributed to the low screw misplacement rate in the 3D group. In our university, we are not able to use a navigation system for screw placement. The 3D model system could be useful to help in accurate screw placement in clinics where the navigation system cannot be used during spinal surgery. Although fluoroscopy was used to assess the accuracy of the implanted pedicle screw during the operation, only CT scans can accurately show vertebral body and medial pedicle cortical violations. This could explain the screw misplacement results of both groups in the study despite the revision with fluoroscopic evaluation.

The selection of appropriate screw size by vertebral level is key for the successful placement of the pedicular screw. Pedicle diameters and corpus depths can be calculated on the vertebral CT axial images, and screw projections in planned levels can be marked on images prior to surgery. With this method, the pedicular screw size can preoperatively be evaluated on the CT axial images of the patients. However, Solitro[34] stated in his review article that commonly accepted criteria for pedicle screw diameter selection have not yet been proposed. Screw diameters of approximately 80% of the pedicle width have been adopted, but this proportion is rarely reported especially in the midthoracic vertebrae for smaller pedicles. Besides CT evaluation, the 3D model can also help in the choosing of the right size of screws with the appropriate angle of approach at the time of operation during implantation. In our study, the patient-specific 3D models guide the appropriate choice of screw length-diameter together with the angle of approach (screw trajectory) while implanting pedicle screws during surgery. Moreover, in the 3D model-assisted surgery group, virtual models of the inserted pedicle screws were used with the generated report to make the instrumentation inventory ready for operation.

In our study, the resident doctors had more positive perceptions stating that they found a 1 : 1 solid model to be beneficial. The mentioned benefits included reducing the number fluoroscopies, easing the preoperative preparation plan and the intervention needed, shortening the operation time, deciding the pedicle screw sizes and the rod lengths, and providing brief visual surgery to patient relatives. Surgeons think that digital images (such as plain film or CT) are too complicated to understand in some situations, but 3D models can resolve it by showing the pathology in detail. The 3D spine model is helpful for surgeons in cases with complex spinal anatomy and will increase the accuracy of pedicle screw implantation. Stimulating the surgery on the 3D model is helpful in surgical training for new generation spine surgeons. Moreover, for experienced surgeons, it is useful to explain complicated surgical techniques to resident doctors before surgery.[2]

Some surgeons, who have no previous experience with a 3D model, believe that evaluating a 3D reconstruction of a CT scan of pathology on a computer screen will be the same as the data they get from a 3D model of the same pathology they hold in their hands. It may be to some extent correct for experienced surgeons. However, Marconi et al[35] specified in their research that despite the 3D reconstructions available with volumetric CT and MRI imaging, the depiction of 3D complex fractures on a 2D monitor is a restriction that can be resolved by the application of 3D models, showing features such as fracture depth and extent more vividly than traditional visualizations. Although there is a lack of information in the literature about the benefits of the 3D model on the screw trajectory during implantation without patient-specific drill guides and templates for pedicle screw placement, 3D model benefits mentioned above could explain simulating the surgery preoperatively in order to guide the appropriate choice of screw length-diameter along with the angle of approach (screw trajectory) while implanting pedicle screws during surgery can contribute to the low screw misplacement rate of even an experienced surgeon during surgery.

Although we conducted our study in the A0 spine type-C fractures, we think that preoperative surgical planning and doing the surgery with a 3D model will provide similar benefits at the time of surgery in all vertebral fracture types. Surgery assisted with a 3D model in the treatment of all types of thoracolumbar spine fractures can exhibit shorter operation duration, less blood loss volume, less fluoroscopy, and more accurate pedicular screw placement.

There were some limitations in our study. It was a randomized noncontrolled study and included perioperative interventions instead of the long-term clinical outcomes. Further research is needed, especially randomized controlled trials in similar fields, to further deepen our understanding of the benefits of 3D printing in the treatment of type-C thoracolumbar spine fractures and its application in daily clinical practice. For clinical application, large volumes of the patient population are needed.

In this study, 3D model-assisted surgery was found to be helpful in preoperative planning and resident education. Patient-specific spine models used for investigating fracture anatomy does not only provide trainees the opportunity to practice their surgical skills before entering the operating theater but also help in choosing the right size of screws with the appropriate angle of approach at the time of operation during implantation. The 3D model can make the placement of pedicle screws by freehand technique in severe spinal trauma cases safer and with acceptable accuracy, thereby reducing operation time, estimating blood loss, and reducing intraoperative fluoroscopy during surgery.

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Informed Consent: Written informed consent was obtained from all participants who participated in this study.

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