The Place of 3D Printing Preoperative Planning in Upper Thoracic Fractures

Ismail Kaya (dr.ikaya85@gmail.com)
Kutahya Health Sciences University, Medical Faculty, Department of Neurosurgery

Ilker Cingoz
Kutahya Health Sciences University, Medical Faculty, Department of Neurosurgery

Meryem Sahin
Kutahya Health Sciences University, Research and Training Center

Emirhan Bozoglan
Kutahya Health Sciences University, Research and Training Center

Murat Sayin
Katip Çelebi University, Medical Faculty, Department of Neurosurgery

Nurullah Yuceer
Katip Çelebi University, Medical Faculty, Department of Neurosurgery

Research Article

Keywords: 3D printing, pedicle screw, preoperative plan, upper thoracic trauma

Posted Date: January 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-138284/v1

Abstract

Background: This study aims to compare the clinical results of patients with upper thoracic vertebral fractures treated with pedicle screw and posterior spinal fusion with preoperative surgical planning and 3-dimensional (3D) modeling and patients treated with freehand screws.

Methods: Thirty patients who underwent pedicle screw placement with a diagnosis of upper thoracic fracture between June 2018 and October 2020 were included in our study. Pedicle screws were used in 15 patients (group 1) after the planning was completed with the help of 3D preoperative printing and modeling. Pedicle screws were applied in 15 patients in the control group (group 2) using the freehand technique. Intraoperative bleeding amount, pedicle screw insertion time, and correct screw placement data in both groups were recorded. The time of insertion of each pedicle screw was recorded.

Results: The operation time was 134 ± 22 minutes for group 1 and 152 ± 38 minutes for group 2. The difference in operation times was found to be statistically significant ($p < 0.05$). Based on axial and sagittal reconstruction images, the accuracy rate of pedicle screw placement (grade 0 and 1) in group I was 96.5% compared to 84.2% in group II. Analyzing axial reconstruction images alone, the overall perforation rate was 10.3% in group I compared to 26.3% in group II. The minor perforation rate (Grade 1, <2 mm) was 7.0% in group I compared to 12.2% in group II. The moderate perforation rate (grade 2, 2-4 mm) was 3.4% in group I compared to 14% in group II. The severe perforation rate (grade 3, > 4 mm) was 1.7% in group II. The difference in overall accuracy rates between the two groups was significant ($p<0.05$).

Conclusions: For 3D models of upper thoracic pedicle screw insertion, guide plates can be produced inexpensively and individually. It provides a new method for the accurate placement of upper thoracic pedicle screws with high accuracy and secure use in screw insertion.

1. Introduction

Spinal cord injuries are common in patients with upper thoracic vertebral fractures due to the smaller diameter of the spinal canal compared to the cervical and lumbar regions. Posterior screw fixation is applied in the upper thoracic region and is used in trauma, segmental instability, kyphosis, scoliosis, infection, and tumor treatments (1, 2). Pedicle screw fixation provides rigid intervertebral fixation but may cause complications, such as artery injury, nerve root damage, and dural damage (3, 4).

Advantages of surgical stabilization in upper thoracic vertebral injuries are correction of sagittal and coronal balance and neurological decompression in kyphotic fractures. Additionally, fixation and fusion prevent hyperkyphosis. Anatomical studies indicate that thoracic pedicle screw insertion in the upper segments is more difficult than that in the lower segment due to the narrower diameter of the pedicles (5). Moreover, the visualization of the upper thoracic region by X-ray and C-arm fluoroscopy during surgery is limited. This limitation of imaging in the preoperative period increases the risk of screw malposition. It has been reported that there is a screw malposition in between 25% and 43% of pedicle screws applied with the freehand technique in the thoracic spine. Recently, thoracic vertebral pedicle screw applications have been performed with the aid of navigation, but failure rates have been detected in 11% of these applications (6, 7).

Currently, 3-dimensional printing technology is used in the preoperative evaluation of patients' anatomy, prosthesis, and implant applications. 3D printers help to increase surgical success by providing a preoperative simulation of surgical approaches (8, 9). Models created with 3D compression are used in medical and surgical fields, such as cranial surgery, maxillofacial traumas, tissue engineering, chest deformities, and complex spine surgery (8, 10).

Creating patient-specific 3D printing models reduces complications during surgery by providing the surgeon with preoperative surgical planning and application. This study aims to compare the clinical results of patients with upper thoracic vertebral fractures treated with pedicle screw and posterior spinal fusion with preoperative surgical planning and 3D modeling and patients treated with freehand screws.

2. Materials And Methods

Thirty patients who underwent pedicle screw placement with a diagnosis of upper thoracic fracture between June 2018 and October 2020 were included in our study. Pedicle screws were applied in 15 patients (group I) after planning was completed with the help of 3D preoperative printing and modeling. Pedicle screws were applied in 15 patients in the control group (group II) using the freehand technique. Modeling and suppression were performed in the Kutahya Health Sciences University Application and Research Laboratory.

Inclusion Criteria

Patients between the ages of 18–65 years who had posterior transpedicular screw application due to upper thoracic fracture (T1-T6) and whose informed consent was obtained were included in the study.

Exclusion Criteria

Patients who had undergone thoracic spine surgery and had a history of thoracic vertebral tumor were excluded from the study.

Digital Design and 3D Printing

Preoperative and postoperative computed tomography (CT) images of 15 patients diagnosed with an upper thoracic fracture in the Neurosurgery Clinic were used for 3D models. Preoperative and postoperative Digital Imaging and Communications in Medicine (DICOM) images of each patient were reconstructed using 32-channel computed tomography at a slice thickness of 0.625 mm and a planar resolution of 0.35 mm (Aquilion™ Large Bore CT, Canon Medical Systems, Tustin, USA) (Figs. 1 and 2).

CT images containing approximately 450 sections for each model were transferred to the 3DSlicer (version 4.10.1, Boston, MA, USA) program to create a 3D vertebral model. Using this software, the images were used to create 3D models of the vertebral region related to the complex surface treatment method. Whereas only the vertebral model was created from preoperative DICOM images, both vertebral and pedicle screw models were created from postoperative DICOM images (Fig. 3).

3D model data were saved in stereolithography (STL) format and transferred to Ultimaker Cura (version 4.7.1) (Ultimaker B.V., Utrecht, Netherlands) software. Two different plans were made for printing the preoperative and postoperative vertebral models in Ultimaker Cura software. The following printing parameters were used for Ultimaker 2 Extended 3D printer and polylactic acid (PLA) in Ultimaker Cura software for the printing of preoperative models: 0.4 mm nozzle diameter, 200 °C nozzle temperature, 70 °C build plate temperature, and 70% filling rate (Fig. 4).

3D models of the postoperative vertebrae and pedicle screws were created separately in 3DSlicer software. 3D models of vertebrae and pedicle screws were saved in STL format and transferred to Ultimaker Cura software. In Ultimaker Cura software, a postoperative life-size model was obtained by merging the vertebra and pedicle screw model. Printing parameters have been updated for the Ultimaker 3 Extended 3D printer with the double nozzle. Two different colored PLA filaments were used for simultaneous printing of vertebrae and pedicle screws (Fig. 4). At this stage, the printing parameters were adjusted to be the same in both nozzles. The following postoperative printing parameters were used: 0.4 mm nozzle diameter, 200 °C nozzle temperature, 70 °C build plate temperature, and 70% filling ratio.

Preoperative planning studies were carried out by the relevant surgeon on vertebra models created using preoperative DICOM images (Figs. 5).

In the postoperative vertebra and pedicle screw models, the appropriateness of postoperative screw positions for surgical planning was examined (Fig. 6).

Operational Methods

Patients' operations were performed by the same surgeons. Preoperative modeling and planning of the patients to be operated on was done with the help of 3D printing and modeling methods. Patient-specific full-scale spine models were available for reference at the time of surgery. Pedicle screws were placed from anatomic regions previously determined by planning and checked with fluoroscopy. In the control group patients, pedicle screws were placed using the freehand technique and under fluoroscopic control.

Evaluation of Efficacy

Intraoperative bleeding amount, pedicle screw insertion time, and correct screw placement data in both groups were recorded. Intraoperative bleeding was calculated by subtracting the volume of fluid used for flushing from the total fluid volume in the suction bag. The time of insertion of each pedicle screw was recorded.

A control CT scan was performed after the operation. Screw malpositions and violations of the medial and lateral walls of the pedicles were noted. The position of the screws was evaluated according to the Gertzbein classification (13). In this classification, there are four categories for screw placement: grade 0, screws are completely within the pedicle; grade 1, perforation < 2 mm; grade 2, perforation between 2 and 4 mm; and grade 3, perforation > 4 mm. In the current study, grades 0 and 1 were considered satisfactory, whereas grades 2 and 3 were regarded as perforated.

Statistical Analysis

The statistical analysis was performed using SPSS 24.0 (IBM Corp.; Armonk, NY, USA) software. Data are presented as the mean ± SD (x ± s), and intergroup comparisons were performed with independent-samples t-tests. The enumeration data are expressed as a ratio, and intergroup comparisons were performed with the chi-square test; p = 0.05 was used as the statistical inspection standard.

3. Results

As a result of our experience in 3D modeling and printing, it took approximately 40 minutes to prepare a model for the T1-T6 vertebrae. Modeling a single thoracic vertebra took approximately 1 hour. As printing time varies according to the model volume, printing for each vertebra was completed after 1.5-2 hours. The printing of the preoperative T1-T6 vertebrae was completed in 12 hours, and the postoperative T1-T6 vertebrae and pedicle screws were completed together in approximately 20 hours.

Of the 30 patients diagnosed with upper thoracic fractures, 15 were female, and 15 were male. The mean age of these 30 patients was 37.3 ± 5.9 years. No statistically significant difference was found between the groups in terms of age and gender (Table 1).

Table 1
Comparative demographic data of both groups.

	Group 1	**Group 2**	**p Value** *
Number of Patients	15	15	-
Sex	8 Male/7 Female	7 Male/8 Female	0,184
Age	36,4 ± 6,2	38,1 ± 5,7	0,260

* *Compared with between group 1 and group 2*

Based on axial and sagittal reconstruction images, the accuracy rate of pedicle screw placement (grades 0 and 1) in group I was 96.5% compared to 84.2% in group II (Table 2). Analyzing axial reconstruction images alone, the overall perforation rate was 10.3% in group I compared to 26,3% in group II. The minor perforation rate (grade 1, < 2 mm) was 7.0% in group I compared to 12.2% in group II. The moderate perforation rate (grade 2, 2–4 mm) was 3.4% in group I compared to 14% in group II. The severe perforation rate (grade 3, > 4 mm) was 1.7% in group II; however, misplaced screws were not associated with neurological deficits (Table 2).

Table 2
Classification of patients according to Gertzbein scoring.

Misplacement (according to Gertzbein's classification)	**Group 1 (n = 116 screws)**	**Group 2 (n = 114 screws)**
Grade 0 (screws are copmletely within the pedicle)	104 (89.6%)	82 (71.9%)
Grade 1 (screw perforation < 2 mm)	8 (7.0%)	14 (12.2%)
Grade 2 (screw perforation between 2–4 mm)	4 (3.4%)	16 (14%)
Grade 3 (screw perforation > 4 mm)	-	2 (1.7%)
Accuracy ⊠	96,5%	84,2%
*⊠ Accuracy = (grade 0 + grade 1)/n * 100%*		

The difference in overall accuracy rates between the two groups was significant ($p < 0.05$)..

The operation time was 134 ± 22 minutes for group 1 and 152 ± 38 minutes for group 2. The difference in operation times was found to be statistically significant ($p < 0.05$) (Table 3). The amount of blood loss for group 1 was 962 ± 108 mL. For group 2, it was 992 ± 114 mL. The difference in the amount of blood loss was not statistically significant ($p > 0.05$) (Table 3).

Table 3
Surgical data.

	Group 1 (n = 15)	**Group 2 (n = 15)**	**P Value ⊠**
Operation Time (min)	134 ± 22	152 ± 38	$p < 0.05$
Blood Loss (mL)	962 ± 108	992 ± 114	$p > 0.05$

Of the 15 upper thoracic fracture patients (group 1), 2 (13.3%) were T3, 5 (33.3%) were T4, and 8 (53.3%) were T6 fractures, which were operated on by 3D modeling with preoperative planning. For these 15 patients, the concordance rate between pedicle positions studied on preoperative models and postoperative pedicle screw positions was 93.8% for T3 fractures, 94.7% for T4 fractures, and 98.4% for T6 fractures (Table 4).

Table 4
Compliance of preoperative planning (Group 1) with postoperative pedicle screw positions in the vertebral model.

Vertebral Model with Fracture Diagnosis	Pedicle Screw Size	Number of Pedicle Screws Inserted	Model Integrity Rate
T3	4.0 × 26 mm	16	93.8%
T4	4.0 × 26 mm	38	94.7%
T6	6.0 × 45 mm	62	98.4%

4. Discussion

Upper and middle thoracic fractures are rare among spinal fractures. Approximately 10–20% of general spinal traumas are observed in this region (12). Upper thoracic vertebral injuries often result in axial stress and bending with rotation and dislocation. This type of injury is generally seen at T4-T6 levels in motorcycle riders (13).

With the development of spine surgery, posterior thoracic interpedicular screwing has become more important. The key to this operation is the correct placement of the pedicle screw in one step, but it has been difficult due to safety concerns relating to the upper thoracic pedicle properties. The upper thoracic spine pedicles are thinner, and there are different angles for each spine. Thoracic pedicles are thin, short, and narrow, and their cortex is thin and fragile; therefore, thoracic pedicles are easily broken during screwing (14). Additionally, the angles of the thoracic pedicles are different from each other, which has made the rate of error in placing thoracic pedicle screws at one time very high, causing serious consequences by damaging the surrounding tissues (15).

The anatomy of the thoracic pedicles is more complex, and screw insertion is more difficult in complex thoracic fractures and vertebral malformations. The penetration rate can reach 30–40% in the insertion of the thoracic pedicle screw with the freehand technique (16). CT-based navigation systems are used to guide the placement of pedicle screws on the spine. However, the accuracy of the systems is questioned, and the failure rate is high (8.5–11%). Its use is not common due to its disadvantages, such as intraoperative position changes and spinal instability, lack of real-time navigation, and high cost (17).

With the use of 3D printing in spine surgeries, the production of guide plates, and provision of preoperative simulation, the accuracy of operations has increased. The fact that the accuracy is not affected by the intraoperative position and the higher reliability of guide plates provides superiority to navigation systems. Providing preoperative simulation and using the model as a guide during surgery reduce the surgeon's margin of error and operation time (18).

Controls performed with 2D fluoroscopy in upper thoracic interpedicular screwing show high error rates. Feyza Karagöz et al. retrospectively examined 113 pedicle screws between T2-T8 in 24 patients without coronal deformity. The control of the pedicle screws was checked during the operation by C arm fluoroscopy and postoperative CT. The faulty pedicle screw insertion rate was found to be 20.3%, 27.4% between T2-T5 and 14.5% between T6-T8 (19). Pedicular screws were applied to T4-T12 levels by 5 experienced surgeons on 5 fresh cadavers - Vaccaro et al. In postoperative CTs, a faulty screw placement rate was found at a rate of approximately 41%. Of these, 21 screws were observed to be in the vertebral canal by preparing the medial wall of the pedicle (20). In our study, in patients who underwent surgery using the freehand technique, a total of 18 (15.7%) incorrect pedicular screw placements were observed, 16 screw grade 2 (14%) and 2 screw grade 3 (1.7%).

With the application of 3D compression in spine surgeries, personalized production of guide plates, and preoperative simulation of the operation on the model have increased the accuracy of operations. The relatively easier and cheaper operating processes and the high reliability of the guide plates have removed the limitations of navigation methods. Lu et al. used 3D modeling as an aid to cervical pedicle or vertebral plate screw placement and proved that it can provide correct placement of the screws (21). Customized 3D spine models and screw insertion guide plates can be used to aid screw insertion and ensure the correct insertion of screws.

Mizutani et al. designed 3D models to apply cervical pedicle screws and achieved good results with guide plates in placing cervical pedicle screws (22). Sugawara et al. created personal 3D navigation models for thoracic pedicle screws and applied pedicle screws under their guidance simply and safely. In 103 patients, 813 screws were placed with 3D guides. In postoperative CT scans, 801 screws (98.5%) were placed without cortical violation, and no injury to the vessels and nerves was observed (23). Wei Hu et al. placed 56 pedicle screws in 7 patients with upper and middle thoracic trauma using the 3D printing-supported preoperative plan method. Regarding the placement of 56 screws according to postoperative CT images, 33 were grade 0, 18 were grade 1, 4 were grade 2 (perforated sidewall), and 1 was grade 3 (perforated sidewall, no vascular nerve injury). The accuracy rate was 91% (24). In our study, screw placement was performed according to postoperative CT images of 116 pedicle screws placed in the upper thoracic spine in 15 patients with preoperative 3D printing support and guidance, and 104 (89.6%) were grade 0, 8 (7.0%) were grade 1, and 4 (3.4%) were grade 2. Grade 3 positioning was not observed in any screw, and the pedicular screw placement accuracy rate was 96.5%. Comparing the pedicle screw placement accuracy of the upper thoracic vertebrae (96.5%) and the pedicle screw placement accuracy (84.2%) of the freehand technique in the 3D printing-supported group, the difference was statistically significant ($p < 0.05$).

In the study by Yue Pan et al., 37 patients with spinal deformities were operated on, with group 1 (20 patients, 396 screws) supported by 3D printing and group 2 (17 patients, 312 screws) supported by the freehand method. The operation time in group 1 was 283 ± 22.7 minutes. In group 2, it was 285 ± 25.8 minutes. The operation time was found to be shorter in group 1, although the difference was not statistically significant ($p = 0.89$) (25). In our study, whereas the operation time was 134 ± 22 minutes for group 1, it was 152 ± 38 minutes for group 2. The difference in operation times was statistically significant ($p < 0.05$).

In the study by William Clifton et al., for 40 C7, 40 T6, and 40 L5 pedicle screws, the rate of agreement between the pedicle positions studied on preoperative models and the postoperative pedicle screw positions was found to be 100% for C7, 100% for T6, and 93% for L5 (26). In our study, 2 (13.3%) of the 15 upper thoracic fracture patients (group 1) were T3, 5 (33.3%) were T4, and 8 (53.3%) were T6 fractures, which were operated on by preoperative planning using 3D modeling. For these 15 patients, the concordance rate between pedicle positions studied on preoperative models and postoperative pedicle screw positions was 93.8% for T3 fractures, 94.7% for T4 fractures, and 98.4% for T6 fractures.

For spinal surgeons, it takes a long time to experience an upper thoracic pedicle screw. Additionally, vertebral canal violations and vascular injuries are common in this region (27). Thanks to the preoperative surgical simulation of the 3D printing-supported model, the application of the upper thoracic pedicle screw will become more efficient and easier. In this study, the accuracy rate obtained in the 3D printing-supported group was 96.5%, which was higher than that of the freehand technique group. We think that the 3D printing-supported method in upper thoracic pedicle screw application will shorten learning time, provide easier learning on the model, and increase pedicular screw placement accuracy.

5. Conclusion

For upper thoracic pedicle screw insertion 3D models, guide plates can be produced inexpensively and individually. It provides a new method for accurate placement of upper thoracic pedicle screws with high accuracy and comfortable use in screw insertion.

Abbreviations

3D
Three Dimensional; T:Thoracic Vertebrae; DICOM:Digital Imaging and Communications in Medicine.

Declarations

Acknowledgements

Not applicable.

Authors’ contributions

IK, IDC, MS and MCS contributed to study conception and design. EB performed the analyses with guidance from NY. IK drafted all sections of the manuscript in consultation with all authors. All authors provided critical input regarding interpretation of results and discussion. All authors revised the article critically for important intellectual content and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Ethics approval

The study was approved by the Kutahya Health Sciences University Clinical Ethics Committee and was conducted following the Helsinki Declaration principles. Written informed consent was obtained from each patient after the study was described.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

References

1. Liljenqvist UR, Halm HF, Link TM. Pedicle screw instrumentation of the thoracic spine in idiopathic scoliosis. Spine (Phila Pa 1976) 1997;22:2239–45.
2. Abumi K, Kaneda K. Pedicle screw fixation for nontraumatic lesions of the cervical spine. Spine (Phila Pa 1976) 1997;22:1853–63.
3. Liljenqvist U, Hackenberg L, Link T, et al. Pullout strength of pedicle screws versus pedicle and laminar hooks in the thoracic spine. Acta Orthop Belg 2001;67:157–63.
4. Vaccaro AR, Rizzolo SJ, Balderston RA, et al. Placement of pedicle screws in the thoracic spine. Part II: An anatomical and radiographic assessment. J Bone Joint Surg Am 1995;77:1200–6.
5. Payer M. Unstable upper and middle thoracic fractures. Preliminary experience with a posterior transpedicular correction-fixation technique. J Clin Neurosci. 2005;12(5):529–33.
6. Gelalis ID, Paschos NK, Pakos EE, et al. Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance, and navigation techniques. Eur Spine J 2012;21:247–55.
7. Youkilis AS, Quint DJ, McGillicuddy JE, et al. Stereotactic navigation for placement of pedicle screws in the thoracic spine. Neurosurgery 2001;48:771–8; discussion 778-9.
8. Vakharia VN, Vakharia NN, Hill CS. Review of 3- Dimensional Printing on Cranial Neurosurgery Simulation Training. World Neurosurg. 2016;88:188–98.
9. Lador R, Regev G, Salame K, Khashan M, Lidar Z. Use of 3-Dimensional Printing Technology in Complex Spine Surgeries. World Neurosurg. 2019 Sep 11. pii: S1878-8750(19)32431-3.

10. Xu W, Zhang X, Ke T, Cai H, Gao X. 3D printing- assisted preoperative plan of pedicle screw placement for middle-upper thoracic trauma: a cohort study. BMC Musculoskelet Disord. 2017;18(1):348.
11. Gertzbein SD, Robbins SE (1990) Accuracy of pedicular screw placement in vivo. Spine (Phila Pa 1976) 15:11–14.
12. Hanley EN, Eskay ML. Thoracic spine fractures. Orthop. 1989;12:689–96.
13. Anthes TB, Muangman N, Bulger E, Stern EJ. Upper thoracic spine fracture-dislocation in a motorcyclist.Curr Probl Diagn Radiol. 2012;41(4):128–9.
14. Krag MH, Beynnon BD, Pope MH et al.: An internal fixator for posterior application to short segments of the thoracic, lumbar, or lumbosacral spine. Design and testing. Clin Orthop Relat Res, 1986; 75–98.
15. Lien SB, Liou NH, Wu SS: Analysis of anatomic morphometry of the pedicles and the safe zone for through-pedicle procedures in the thoracic and lumbar spine. Eur Spine J, 2007; 16: 1215–22.
16. Kim YJ, Lenke LG, Bridwell KH et al.: Freehand pedicle screw placement in the thoracic spine: is it safe? Spine (Phila Pa 1976), 2004; 29: 333–42; discussion 42.
17. Gelalis ID, Paschos NK, Pakos EE, Politis AN, Arnaoutoglou CM, Karageorgos AC et al. Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance, and navigation techniques. Eur Spine J. 2012;21:247–255.
18. Chen H, Guo K, Yang H, Wu D, Yuan F. Thoracic Pedicle Screw Placement Guide Plate Produced by Three-Dimensional (3-D) Laser Printing. Med Sci Monit. 2016;22:1682–1686. Published 2016 May 19.
19. Guzey FK, Emel E, Hakan Seyithanoglu M, Serdar Bas N, Ozkan N, Sel B, Aycan A, Alatas I (2006) Accuracy of pedicle screw placement for upper and middle thoracic pathologies without coronal plane spinal deformity using conventional methods. J Spinal Disord tech 19(6):436
20. Vaccaro A, Rizzolo SJ, Balderston RA, et al. Placement of pedicle screws in the thoracic spine. Part II: an anatomical and radiographic assessment. J Bone Joint Surg Am. 1995;77(8):1200–6.
21. Lu S, Xu YQ, Chen GP et al.: Efficacy and accuracy of a novel rapid prototyping drill template for cervical pedicle screw placement. Comput Aided Surg, 2011; 16: 240–48
22. Mizutani J, Matsubara T, Fukuoka M, et al. Application of full-scale three-dimensional models in patients with rheumatoid cervical spine. Eur Spine J. 2008;17:644–649.
23. Sugawara T, Higashiyama N, Kaneyama S, et al. Multistep pedicle screw insertion procedure with patient-specific lamina fit-and-lock templates for the thoracic spine: clinical article. J Neurosurg Spine. 2013;19:185–190.
24. Xu W, Zhang X, Ke T, et al. 3D printing–assisted preoperative plan of pedicle screw placement for middle-upper thoracic trauma: a cohort study. BMC Musculoskelet Disord 2017;18:348.
25. Pan Y., Lü G.H., Kuang L., Wang B. Accuracy of thoracic pedicle screw placement in adolescent patients with severe spinal deformities: a retrospective study comparing drill guide template with freehand technique. Eur Spine J. 2018;27(2):319–326. DOI: 10.1007/s00586-017-5410-2

26. Clifton W, Pichelmann M, Vlasak A, Damon A, ReFaey K, Nottmeier E. Investigation and feasibility of combined 3D printed thermoplastic filament and polymeric foam to simulate the cortiocancellous interface of human vertebrae. Sci Rep. 2020;10:2912.
27. Di Silvestre M, Parisini P, Lolli F, Bakaloudis G.Complications of thoracic pedicle screws in scoliosis treatment. Spine (Phila Pa 1976). 2007;32:1655–1661.

Figures

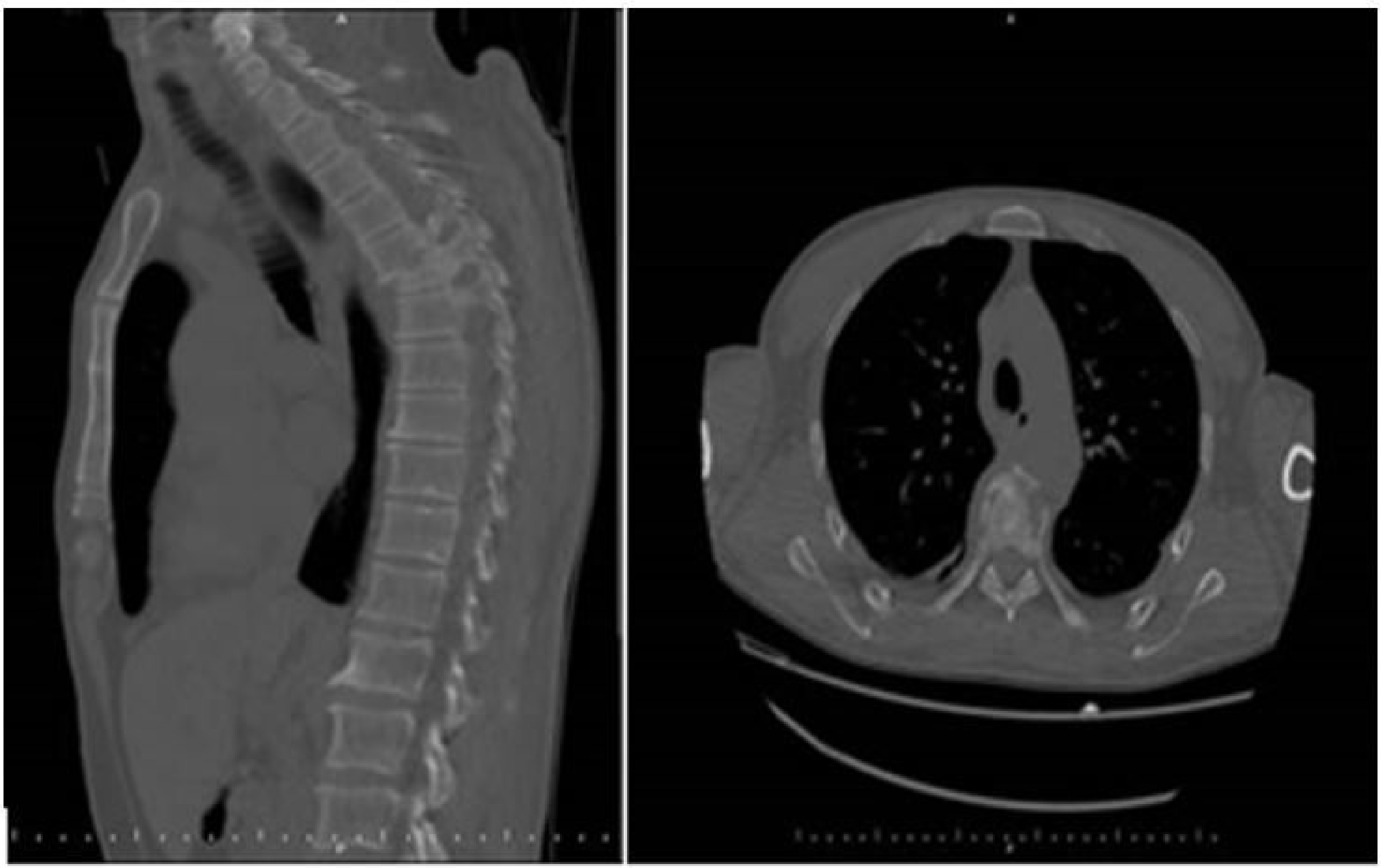

Figure 1

Preoperative CT view of the upper thoracic fracture.

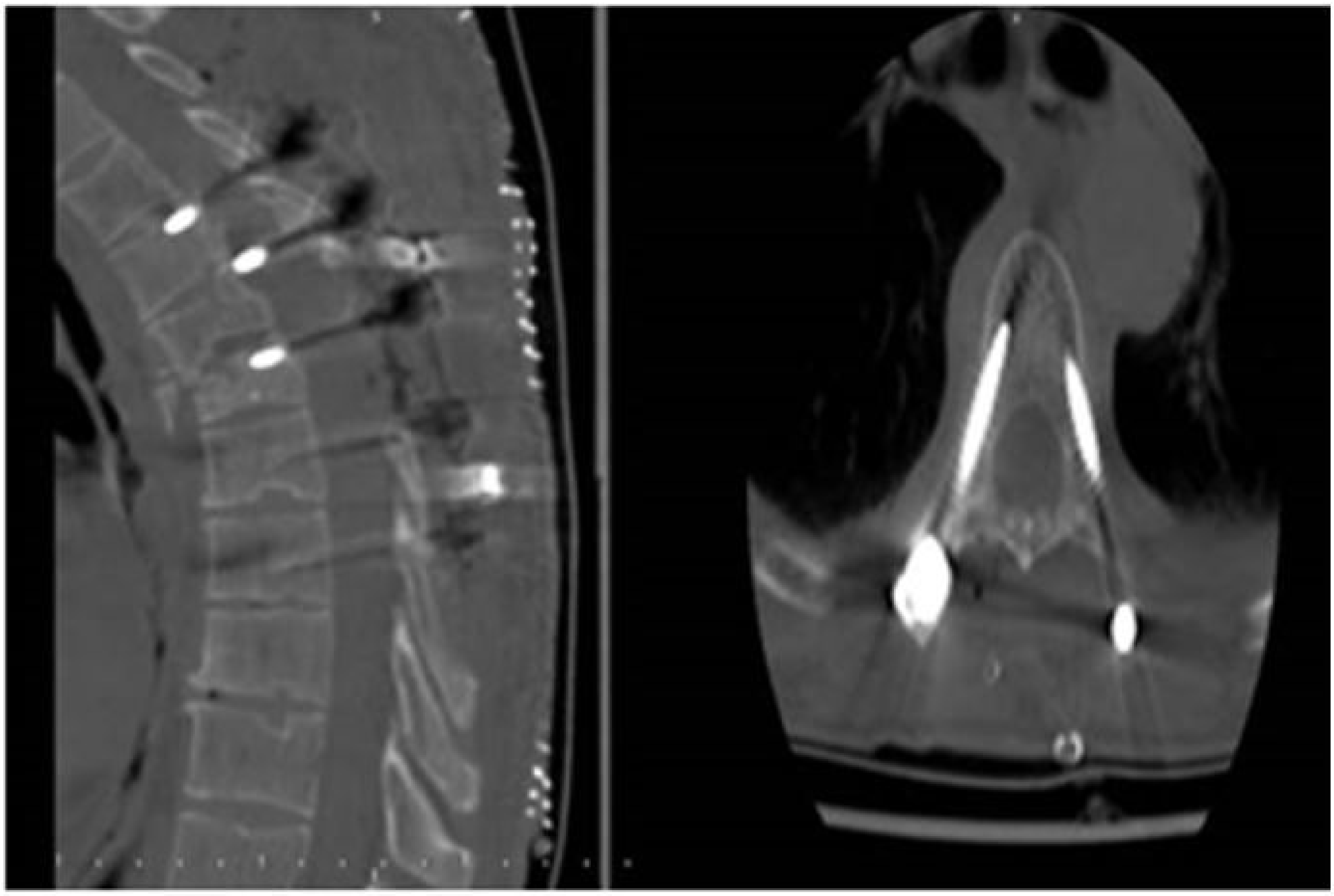

Figure 2

Upper thoracic fracture postoperative CT image.

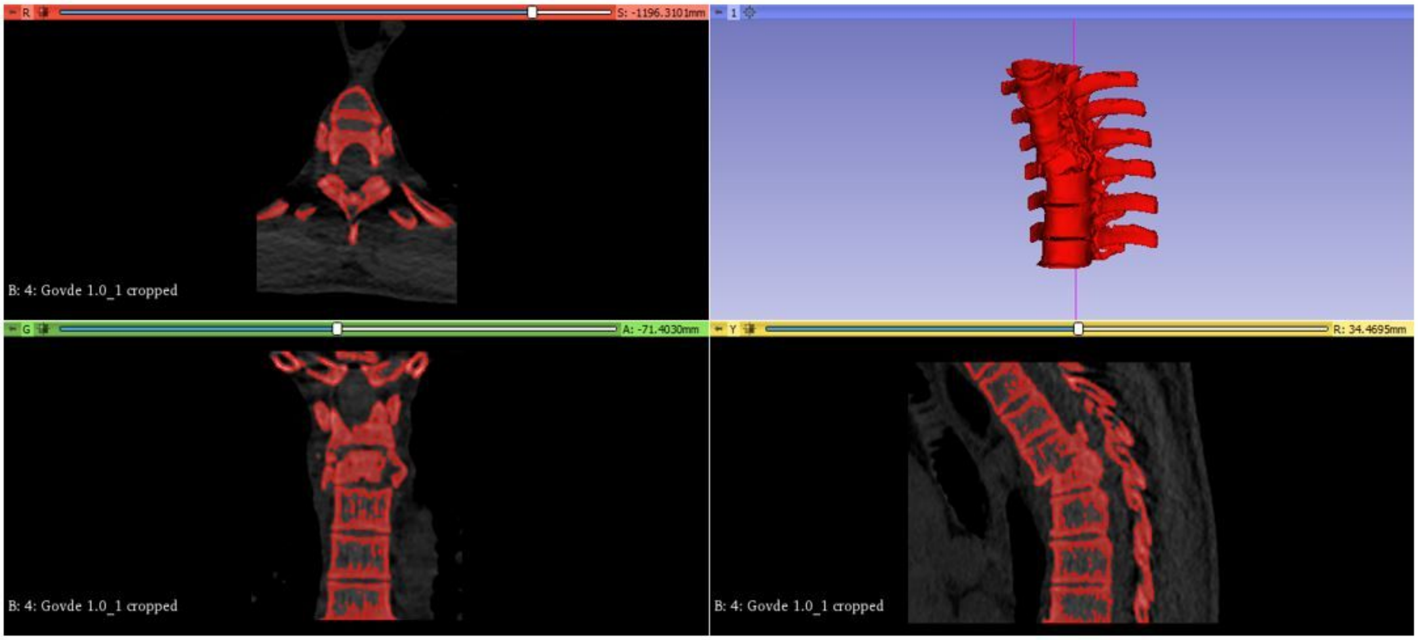

Figure 3

Modeling of the vertebrae in the 3DSlicer program.

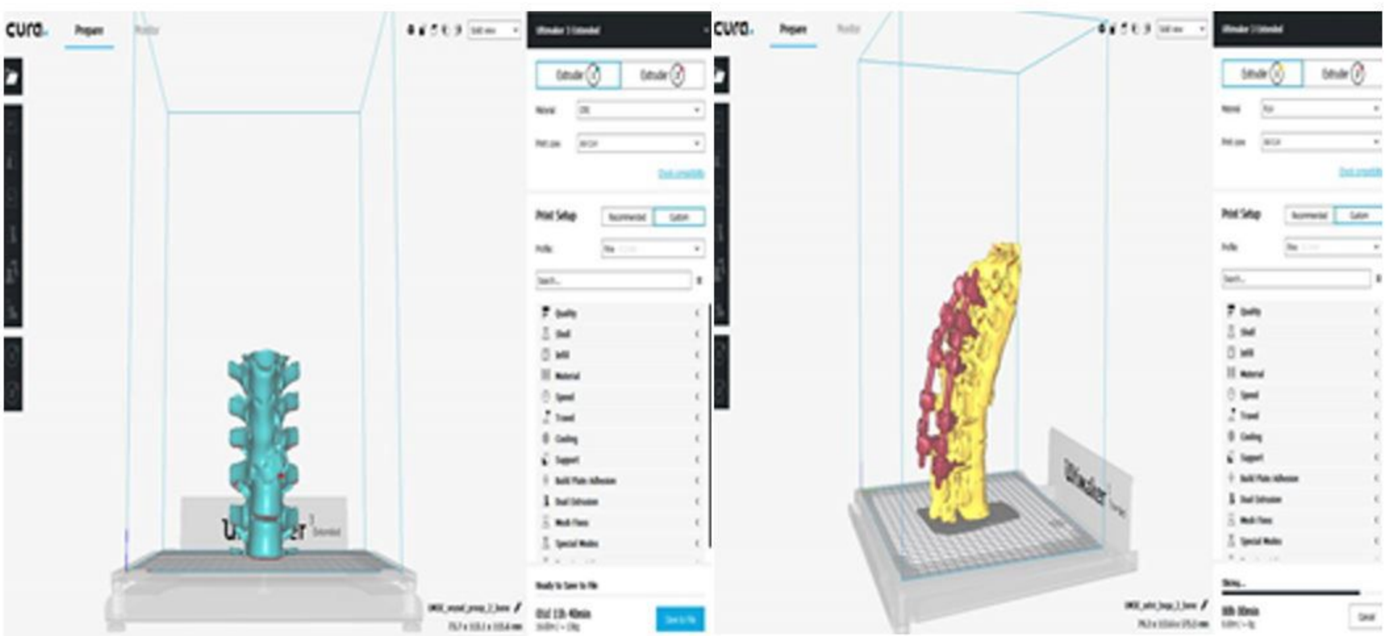

Figure 4

Preparation of printing parameters for preoperative and postoperative models in the Ultimaker Cura program.

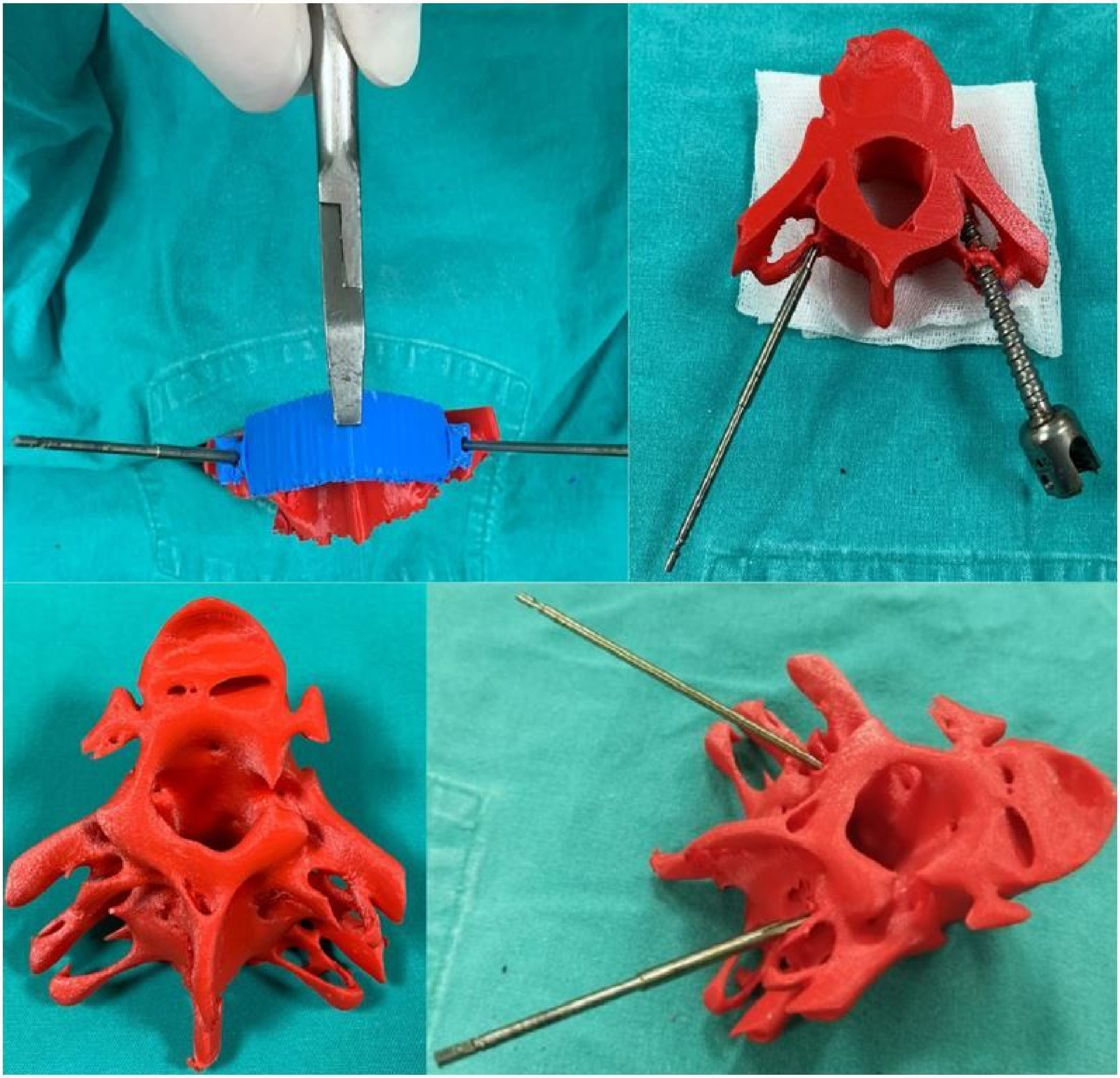

Figure 5

T4-T6 vertebrae prepared for preoperative planning.

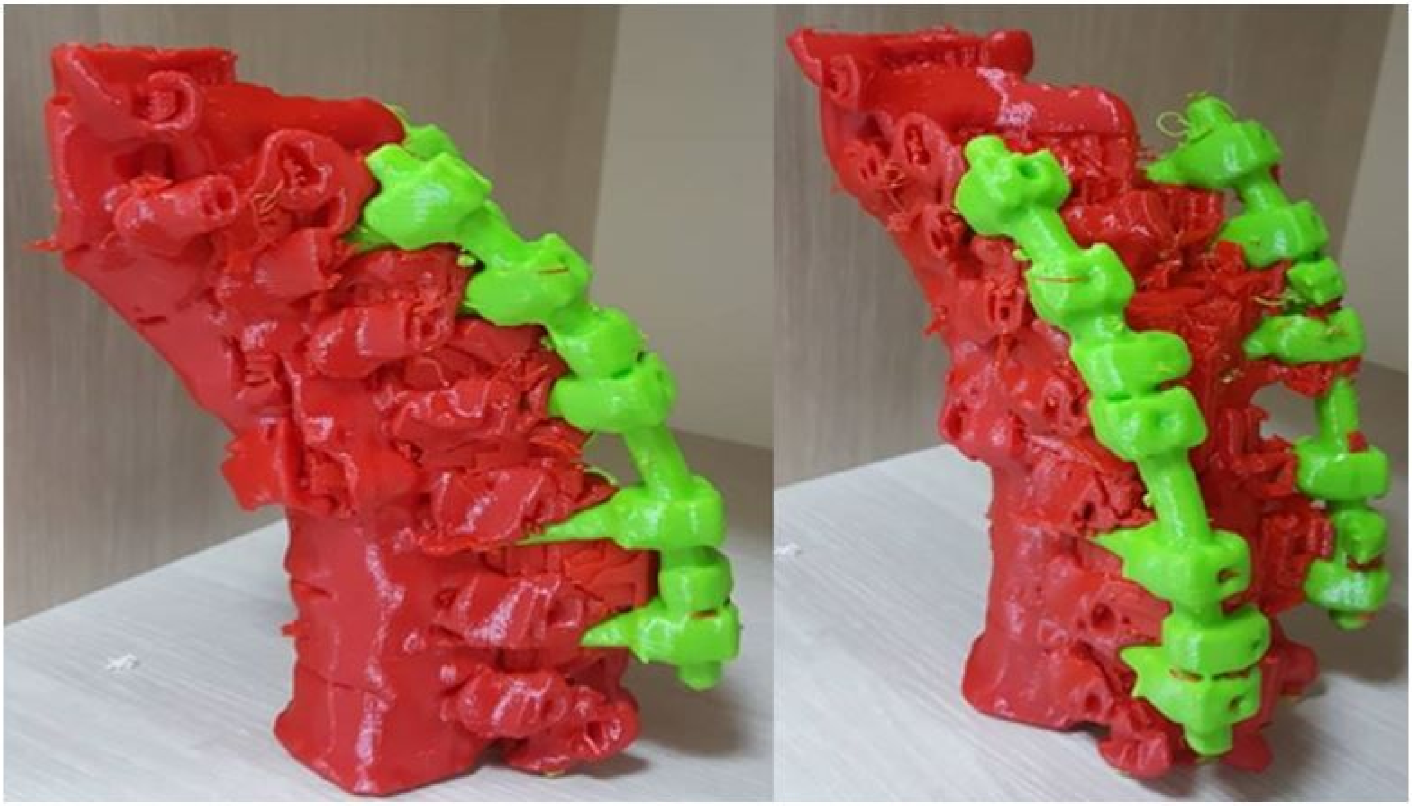

Figure 6

Postoperative pedicle screw placement.