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Original article

# Clinical application of three-dimensional printing in the personalized treatment of complex spinal disorders

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A B S T R A C T

*Purpose:* To investigate the usefulness of three-dimensional (3D) printing in complex spinal surgery.
*Methods:* The study was conducted from October 2014 to March 2015 in Shenzhen Second Peoples' Hospital and 4 cases of complex severe spinal disorders were selected from our department. Among them one patient combined with congenital scoliosis, one with atlas neoplasm, one with atlantoaxial dislocation, and the rest one with atlantoaxial fracture-dislocation. The data of the diseased region was collected from computerized tomography scans for 3D digital reconstruction and rapid prototyping to prepare photosensitive resin models, which were applied in the treatment of these cases.
*Results:* The use of 3D models reduced operating time and intraoperative blood loss as well as the risk of postoperative complications. Furthermore, no pedicle penetrations or screw misplacement occurred according to the postoperative planar radiographic images.
*Conclusion:* The tactile models from 3D printing allow direct observation and measurement, helping the orthopedists to have accurate morphometric information to provide personalized surgical planning and better communication with the patient and coworkers. Moreover, the photosensitive resin models can also guide the actual surgery with the drilling of pedicle screws and safe resection of tumor.


## Introduction

The development of polymer material science, laser technique and computer-aided design, as well as novel materials science has permitted the creation of three-dimensional (3D) printing technology. It reproduces the morphology of the affected spinal segments from computerized tomography (CT) scans with the aid from image processing software and a rapid prototyping equipment to produce a tactile model in various materials.[1] Recently, the 3D printing has been widely employed to build physical models for use in surgical procedures, preoperative planning, personalized prosthesis fabrication and other fields.[2–4]

In complex spinal disorders as scoliosis, the correction procedure is often very challenging as unexpected pedicle absence and vertebral rotations can be discovered intraoperatively, posing great risk of neurovascular lesions during the operation.[5] Apparently, current visualization modalities as planar radiographic image and CT scans are not qualified to provide necessary anatomic overview of the affected spinal segments, even the CT with 3D reconstruction can only provide the image without tactile feedback. Therefore, 3D printing is very promising in the personalized treatment of complex spinal disorders. Nevertheless, few researches have been conducted to study the use of 3D printing on this field. In this study, researchers developed photosensitive resin models for 4 cases of complex spinal disorders to achieve their personalized treatment and investigate the clinical significance of 3D printing.

## Materials and methods

The study was performed in the Department of Spinal Surgery of Shenzhen Second Peoples' Hospital from October 2014 to March 2015. This study has been approved by the hospital review board, and all patients provided informed consent to participate in this study. Table 1 shows the detailed information of the 4 selected cases, all male, for 3D modeling.

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*3D digital spinal reconstruction*

All the patients were selected for 3D modeling process as their pathoanatomy was considered not to be clearly shown by common imaging techniques. The physical models were created on the 3D printer prior to surgery. In brief, a patient's affected region was scanned using a volumetric CT (Somatom Definition AS, Siemens, Japan) with 1-mm slice thickness and 0.24-mm in-plane resolution. The digital imaging and communication in medicine (DICOM) format data sets of the 4 cases were then downloaded from the CT workstation. Each data set was uploaded to a computer with Bio3D software to reconstruct a 3D digital spine wire frame that can be used to obtain all the anatomical information needed. The 3D reconstruction data were transferred to a stereolithography (STL) format file by Bio3D software to construct photosensitive resin models.

*Computer-designed photosensitive resin models*

An STL apparatus uses Stereo Lithography Apparatus (SLA) technology (MP-4500, Shenzhen Ultron 4D Technology Co. Ltd., Shenzhen, China) to build a photosensitive resin model layer by layer. The photosensitive resin is an ultraviolet laser-solidified layer by layer based on the standard STL format file and accumulated to build a 3D model. Each computer-designed photosensitive resin model was manufactured automatically for 9–27 h. It costs about 2000–3000 RMB to create one photosensitive resin model.

*Perioperative treatment planning*

The 3D models were then used for observation of the spinal pathoanatomy, surgical planning, and selection of internal-fixation instruments prior to surgical procedures. Intraoperatively, the physical models were used for the confirmation of the anatomical landmarks and the guidance of the operation. Its accuracy was then evaluated by postoperative plain film radiographs and CT images.

## Results

*Scoliosis surgery*

In the congenital scoliosis case, detailed information of the deformity could not be observed clearly on radiographs because of hemivertebra and rotation (Fig. 1A). After 3D reconstruction of the spine, the malformation could be easily observed from any direction and angle (Fig. 2). The direction and diameter of the pedicle could be roughly determined on the physical model (Fig. 3A). The surgery was performed without severe complications, and the patient started walking with a brace on postoperative 6 days. The postoperative radiograph shows 90.9% correction of scoliosis Cobb angle (Fig. 4A).

*Tumor surgery*

In the upper cervical tumor case, the 7-year-old patient had the tumor resected without the need for stabilization. The operation was performed with the assistance of the 3D model and preoperative CT images (Figs. 1B and 3B). The physical model aided in the determination of tumor extent and its anatomical relations with neighboring structures. Wide resection of the lesion was conducted and iliac crest was obtained to reconstruct the deficit. Pathologic analysis confirmed eosinophilic granuloma and postoperative CT image shows complete tumor resection (Fig. 4B).

*Cervical fracture and dislocation surgery*

The patients were admitted to our department with neck pain and numbness in upper extremities. Preoperative radiograph and CT scan showed the diseased segments (Fig. 1C,D). During the surgery, the screw entry point was determined after direct observation of the 3D models (Fig. 3C,D). The screw insertion procedure was performed under fluoroscopic guidance, and the physical models were used as a complementary. In case 3, the treating surgeons performed bilateral $C_{1-4}$ pedicle screw insertions to obtain rigid fixation. The patient's postoperative course was uneventful. Postoperative radiograph showed appropriate screw position (Fig. 4D).

In case 4, according to the preoperative measurements of the 3D model, the direction of $C_1$ lateral mass screws were changed slightly to avoid cord lesion and the length of the $C_2$ pedicle screws were shortened to avoid vertebral artery injury. With $C_1$ laminectomy, iliac crest chips were implanted for bony fusion. A halo-vest brace was adopted for immobilization of the patients' neck during the perioperative period. The postoperative CT images showed the screws in the pedicle tract without cortical wall perforation (Fig. 4C).

All the surgeries were completed with satisfactory outcomes. The surgeons responded favorably to the use of 3D models due to the reduction of operation time and intraoperative blood loss (Estimates of the time saved and reduction of blood loss were made using historical reference data for equivalent complex spinal disorder cases at the same department). The patients' attitude towards 3D model was also very positive, as it provided them with greater understanding of their situation, surgical plan, and potential risks.

## Discussion

3D printing technology facilitates data sets from CT scans to be present in physical and tactile form. The 3D models are found to be fairly accurate in relation to anatomy. In complex spinal surgery, 3D printing possesses advantages over the use of 2D imaging techniques. Preoperatively, planning the surgical procedure and selecting the internal-fixation instruments were completed according to the observation and measurements of the physical

**Table 1**
Summary of the four selected complex cases.

| ID | Model date | Sex | Age (yr) | Diagnosis | Affected segment | Surgical approach |
|---|---|---|---|---|---|---|
| 1 | Feb 2015 | M | 12 | Congenital scoliosis $L_1$ hemivertebra | Thoracolumbar | Posterior $L_1$ hemivertebra resection, decompression and instrumented fusion $T_{10}$–$L_3$ |
| 2 | Aug 2014 | M | 7 | Eosinophilic granuloma of $C_1$ | Cervical | Transoral endoscopic resection of tumor |
| 3 | Jan 2015 | M | 72 | Fracture dislocation of $C_{1-2}$ | Cervical | Posterior stabilization with pedicle screws, decompression and instrumented fusion $C_{1-4}$ |
| 4 | Apr 2015 | M | 12 | Dislocation of $C_{1-2}$ | Cervical | Posterior stabilization with lateral mass screws ($C_1$) and pedicle screws ($C_2$), $C_1$ laminectomy, decompression and instrumented fusion $C_{1-2}$, halo-vest immobilization |