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Original article

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

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ABSTRACT

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.
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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

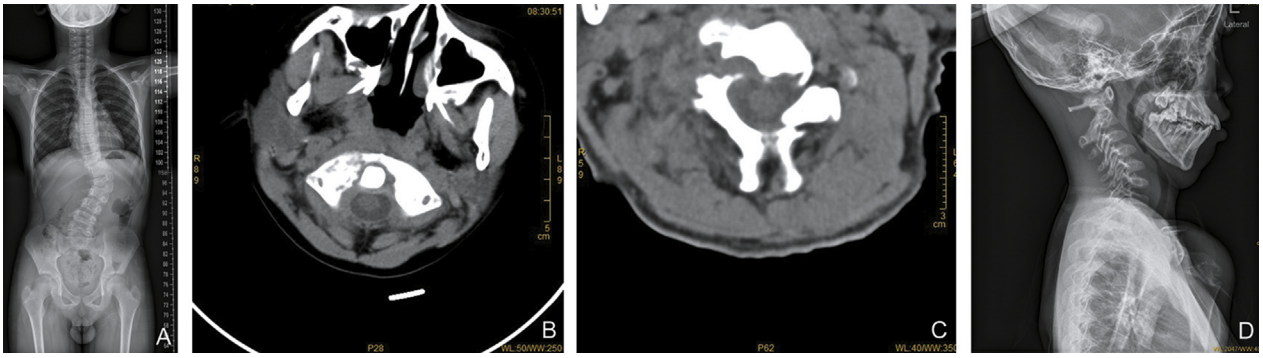


Fig. 1. A: Preoperative posterior–anterior radiograph of case 1 showing a scoliosis Cobb angle of 55°. B: Preoperative CT image of case 2 showing tumor lesion area. C: Preoperative CT image of case 3 showing fracture of cervical vertebrae. D: Preoperative lateral radiograph of case 4 showing cervical dislocation.

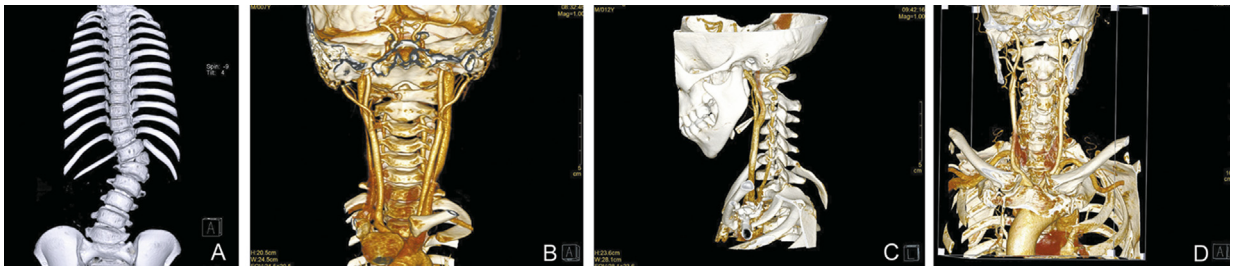


Fig. 2. Digital spinal 3D reconstruction result of 4 cases based on the CT data sets.

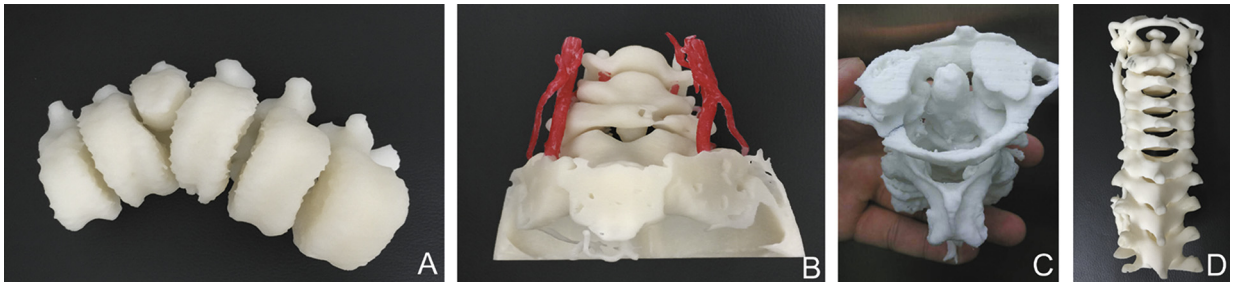


Fig. 3. Rapid prototyping models of four cases.

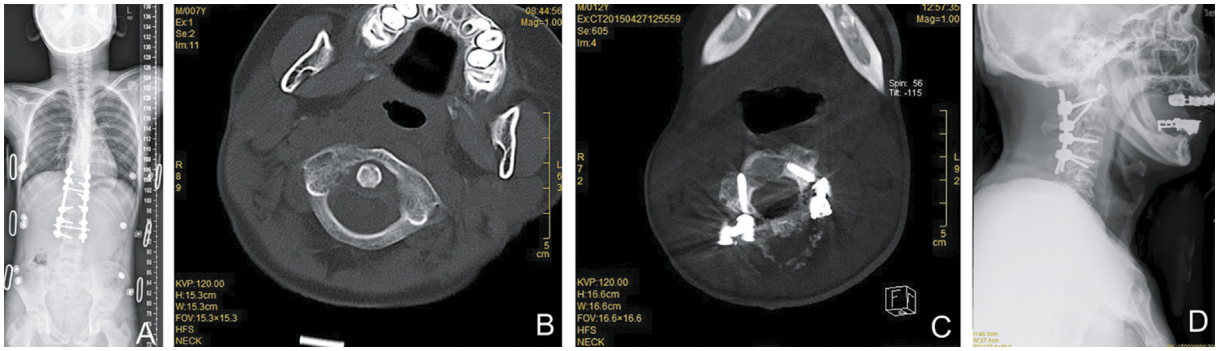


Fig. 4. A: Posterior L_1 hemivertebra resection, decompression and instrumented fusion from T_{10}–L_3 in case 1. Postoperative posterior–anterior radiograph shows 90.9% correction. B: Transoral endoscopic resection of tumor in case 2. Postoperative CT image shows complete tumor resection. C: Posterior stabilization with lateral mass screws (C_1) and pedicle screws (C_2), C_1 laminectomy, decompression and instrumented fusion of C_{1-2} in case 4. Postoperative CT image showed pedicle screws in the pedicle tract, without cortical wall perforation. D: Posterior stabilization with pedicle screws, decompression and instrumented fusion of C_{1-4} in case 3. Postoperative lateral radiograph showed appropriate screw position.

models. Intraoperatively, the model provides surgeons with accurate anatomical information with less frequent reference to other visualization modalities, thus improving the surgical confidence during procedure.

In severe scoliosis cases, anatomic variation as vertebrae rotation and kyphosis pose great challenge to the determination of bony landmarks, thereby complicating the screw placement procedure for surgeons with free-hand technique. Besides, screw misplacement is also a major concern in spinal deformity cases due to its serious neurological and vascular complications.[6] The traditional 2D visualization modalities often fail to provide the necessary morphometric information about the spinal anomalies. In the meantime, the application of 3D reconstruction in complex scoliosis cases is limited due to lacking of tactile feedback.[7] In recent years, intraoperative navigation system seems to obtain affection in medical application,[8] but it is difficult to be widely applied due to its expensive costs and complicated manipulation.[9] Moreover, pedicle violation in scoliosis cases also prevents it from extending in most institutions.[10]

Recently, in the research by Mao et al,[7] 3D printing technology was applied in the treatment of 16 severe scoliosis cases. They believed that the comprehensive anatomic information provided by the 3D models helps surgeons to achieve satisfying results. Moreover, Wu et al[11] compared the use of 3D printing technology with intraoperative fluoroscopy in scoliosis correction surgery, which demonstrated positive effects of 3D models on the improvement of screw placement. In our study, based on the measurements of 3D model, screw entry point, angle and size could be roughly determined preoperatively. And the surgeons were able to assess the rod contour as well as the amount of bony resection prior to operation. Intraoperatively, the surgeon could visualize the anatomical structure of the posterior elements without having to mentally reconstruct 2D images, thus facilitating the surgical procedures. Therefore, with 3D printing technology, the treating surgeons can perform more successful screw insertion and reduce operative time in complex scoliosis cases.

In upper cervical tumor cases, it is challenging to accomplish tumor resection without postoperative complications due to the complex anatomy (vital surrounding structure as medulla oblongata). The common 2D imaging fails to afford accurate information of the tumor pathoanatomy as tumor size and extent, thus complicating the surgical planning and intraoperative procedure. While in cervical fracture and dislocation cases, it is widely accepted to use pedicle screw placement system to reconstruct spinal balance. However, the risk of vertebral artery and neurological lesions has been the major concern with the screw placement system.[12,13] Multiple methods have been proposed to enhance screw placement accuracy, but pedicle perforations still occur.[14] Moreover, as every cervical vertebra has its unique morphology, it is also time-consuming to have frequent reference to common imaging modalities intraoperatively. Therefore, the challenges of tumor resection and pedicle screw placement make the 3D models attractive.

In the study by D'Urso et al,[15] the physical models provided direct visualization of tumors and its relationship with neighboring structures. This allows the surgeons to have the resection of C_2 osteoblastoma in a smooth way. Van Dijk et al[16] reported 4 cases of spinal tumor resection. In their study, after preoperative observation of physical biomodels, personalized surgical planning was made according to tumor size, type, site and other characteristics. And the surgeons were then able to perform safer dissection of tumors with reduced operation time and blood loss. In the research by Yamazaki et al,[17] physical model was used for preoperative observation. Intraoperatively, the anatomical reference provided by the biomodel facilitated the insertion of pedicle screws without injuring neighboring structures.

In our cervical fracture and dislocation case, the 3D printing facilitates the *in vitro* visualization of vertebral artery, which contributes to the modification of screw length and angle during surgical procedures. Thus, the need for intraoperative radiograph to guide placement is reduced. And the consequent reduction of radiograph exposure is quite beneficial to both surgeons and patients. While in our tumor case, with essential anatomical information from the spinal model, surgeons are allowed to perform safe and wide tumor resection with less operation time and blood loss. The effectiveness of physical model in reducing time and blood loss is believed to be greatly significant in more complex tumor cases. Besides, the 3D physical models served as a communication tool, providing the patients with a better understanding of the disorder and of the risks involved in the surgery. Moreover, the 3D models could improve the communication among the surgeons and facilitate the education of young surgeons.

Our study has used 3D printing for deformity, tumor and fracture-dislocation cases with challenging anatomy and confirmed its contribution in the treatment of complex spinal disorders. Compared with other common visualization modalities, the physical models provide better visible and tactile information, reducing the surgical times and risks of screw misplacement. However, the cost of production prevents it from widely applying for educational use. And in aggressive tumor cases, it is still challenging for the printing of soft tissue where tumor invasion often occur, thereby influencing surgeons' estimate of the tumor extent. To conclude, the application of 3D printing proves to pose a positive effect on the treatment of complex spinal disorders, whereas prospective controlled study with larger samples is needed to explore and elucidate the efficacy of this technology.

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