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ORIGINAL ARTICLE

Clinical application of computer-designed polystyrene models in complex severe spinal deformities: a pilot study

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Abstract Surgical treatment of complex severe spinal deformity, involving a scoliosis Cobb angle of more than 90° and kyphosis or vertebral and rib deformity, is challenging. Preoperative two-dimensional images resulting from plain film radiography, computed tomography (CT) and magnetic resonance imaging provide limited morphometric information. Although the three-dimensional (3D) reconstruction CT with special software can view the stereo and rotate the spinal image on the screen, it cannot show the full-scale spine and cannot directly be used on the operation table. This study was conducted to investigate the application of computer-designed polystyrene models in the treatment of complex severe spinal deformity. The study involved 16 cases of complex severe spinal deformity treated in our hospital between 1 May 2004 and 31 December 2007; the mean ± SD preoperative scoliosis Cobb angle was 118° ± 27°. The CT scanning digital imaging and communication in medicine (DICOM) data sets of the affected spinal segments were collected for 3D digital reconstruction and rapid prototyping to prepare computer-designed polystyrene models, which were applied in the treatment of these cases. The computer-designed polystyrene models allowed 3D observation and measurement of the deformities directly, which helped the surgeon to perform morphological assessment and communicate with the patient and colleagues. Furthermore, the models also guided the choice and placement of pedicle screws. Moreover, the models were used to aid in virtual surgery and guide the actual surgical procedure. The mean ± SD postoperative scoliosis Cobb angle was 42° ± 32°, and no serious complications such as spinal cord or major vascular injury occurred. The use of computer-designed polystyrene models could provide more accurate morphometric information and facilitate surgical correction of complex severe spinal deformity.

Keywords Spinal deformity · Severe · Polystyrene models · Rapid prototyping

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Introduction

Complex severe spinal deformity is characterized by a scoliosis Cobb angle of more than 90° combined with scoliosis, kyphosis, vertebral deformity and other complex deformities. It can result from a variety of causes, including congenital spinal malformations, neurofibromatosis, neuromuscular diseases, infantile idiopathic scoliosis and others. If not treated on time, the deformity could progress and even result in marked cosmetic deformity, vital capacity and possible neurologic damage [3, 13]. Surgical correction of this condition is challenging because of unexpected malformations that are often discovered during surgery, and the procedure carries risks of major neurologic damage, vascular injury and other complications [8, 9]. Therefore, obtaining as much information as possible about the malformation before surgery is important. Because of vertebral scoliosis, kyphosis, rotation and other deformities, two-dimensional (2D) images from preoperative plain film radiography, computed tomography (CT) and magnetic resonance imaging (MRI) provide limited morphometric information about the deformity [6, 10]. CT with three-dimensional reconstruction (3D CT) can view the image of the spine in three dimensions on the screen, but not that of a full-scale spine. It does not provide tactile feedback and cannot be used directly on the OR table.

The development of information technology and medicine has permitted the creation of a "digital human being". 3D digital reconstruction based on segmented CT slice data is the main technique employed to build a digital human skeletal system for use in disease diagnosis, new drug research, surgical procedures and many other fields [5, 15, 21]. Rapid prototyping is an advanced manufacturing technique used for quick template fabrication, and some research has been conducted on using it to facilitate the manufacture of spinal instrumentation [7]. No research has been conducted, however, on the use of this method in the treatment of complex severe spinal deformity. In this study, computer-designed polystyrene models were developed by means of 3D digital reconstruction and rapid prototyping for 16 cases of complex severe spinal deformity. The goal was to help the surgeon obtain more accurate and more direct information about the deformity by using an imitated spine in the virtual operation process and increasing the accuracy of insertion of the pedicle screw.

Materials and methods

This study was performed in the orthopaedic department of the General Hospital of Chinese People's Liberation Army between 1 May 2004, and 31 December 2007. Patients with complex severe spinal deformities treated at this institution included 3 patients with idiopathic kyphoscoliosis, 11 with congenital spinal malformations and 2 with neuromuscular disease. This study was approved by the hospital review board, and all patients gave written informed consent to participate. There were 2 male and 14 female patients with an average age of 17.8 years (range 6–38 years) at the time of surgery. A patient had to have a preoperative scoliosis Cobb angle on spinal radiographs of more than 90°, combined with kyphosis or vertebral deformity, to be included in the study. The mean ± SD preoperative scoliosis Cobb angle was 118° ± 27° (range 94°–142°), and the mean ± SD preoperative kyphosis Cobb angle was 87° ± 39° (range 67°–114°).

3D digital spinal reconstruction

A General Electric helical CT scanner (LightSpeed, 16 rows, GE Co. Ltd. USA) with a slice thickness of 1.25 mm and an interval of 1 mm was used to obtain the data for 3D digital spinal reconstruction. The total scanning time ranged from 20 to 40 s, and the scanning field involved all deformity regions. The digital imaging and communication in medicine (DICOM) format data sets of the 16 affected spinal segments were downloaded from the CT GE Advantage workstation.

Each downloaded data set was uploaded to a personal computer with Mimics (Materialise interactive medical image control system) 6.3 software (Materialise, Leuven, Belgium) to reconstruct a 3D digital spine wire frame that could be viewed from any direction and could be used to obtain all of the spinal deformity information, such as pedicle length and transverse and sagittal diameters from various angles and sections. The 3D reconstruction digital spine data were transferred to a stereolithography (STL) format file by Mimics 6.3 software to construct a polystyrene model.

Computer-designed polystyrene models

An STL apparatus uses selective laser sintering (SLS) technology (AFS-450, Beijing Long Yuan Automated Fabrication System Co. Ltd., Beijing, China) to build a computer-designed polystyrene model layer by layer. The polystyrene powder is a laser-fused layer by layer based on the standard STL format file resulting from Mimics 6.3 software and accumulated to create a 3D structural model. All of the spinal deformity information can be viewed more directly from the model, which can be used on the operation table directly after sterilization. It was compared with the results of 3D digital spinal reconstruction and verified during the surgical procedure.

Surgical treatment planning

For each case, planning the surgical procedure and choosing internal-fixation instruments were done according to the preoperative radiographs and 3D digital spinal reconstruction, and the computer-designed model was used as a complementary. Furthermore, a virtual operation was performed on the computer-designed model to imitate and plan the actual procedure, such as osteotomy location, and length and angle of pedicle screw insertion. After it was sterilized with epoxy ethane, the model was viewed on the operating table during surgery and compared with the exposed spine segments. The model's accuracy was evaluated with the surgical procedure as well as postoperative radiographs and CT images.

Results

In all 16 cases of complex severe spinal deformity, surgery was performed without serious complications such as spinal cord or major vascular injury. The patients began walking using a brace on postoperative 4–6 days. The mean ± SD postoperative scoliosis Cobb angle was

42° ± 32° (range 31°–78°), and the mean ± SD postoperative kyphosis angle was 39° ± 27° (range 23°–68°).

Details of the spinal deformities could not be seen clearly on radiographs because of vertebral overlap and rotation (Fig. 1a, b). After 3D digital spinal reconstruction based on the CT data set, the spinal malformation could be clearly observed from any direction and angle (Fig. 2a, b). Detailed information about the deformity was obtained through display and measurement on the personal computer with Mimics 6.3 software, and the direction and diameter of the pedicle were easily measured in any angle of the plane (Fig. 2c, d).

Each computer-designed polystyrene model was manufactured automatically with SLS technology in 5–16 h. It costs about 2,000 RMB (200 €) to create one polystyrene model. Because the model was exactly of the same size as the actual spinal deformity (Fig. 3), it provided a tactile anatomical representation, and the spinal deformity could be observed directly, allowing the surgeon to plan the procedure, simulate the operation process and choose and apply appropriate internal-fixation instruments. Furthermore, the model facilitated communication with the patient and colleagues. During the procedure, the sterilized template was placed on the patient's vertebral side to match the exposed spinal deformity. The model provided guidance for choosing the optimal drilling direction and angle of the pedicle.

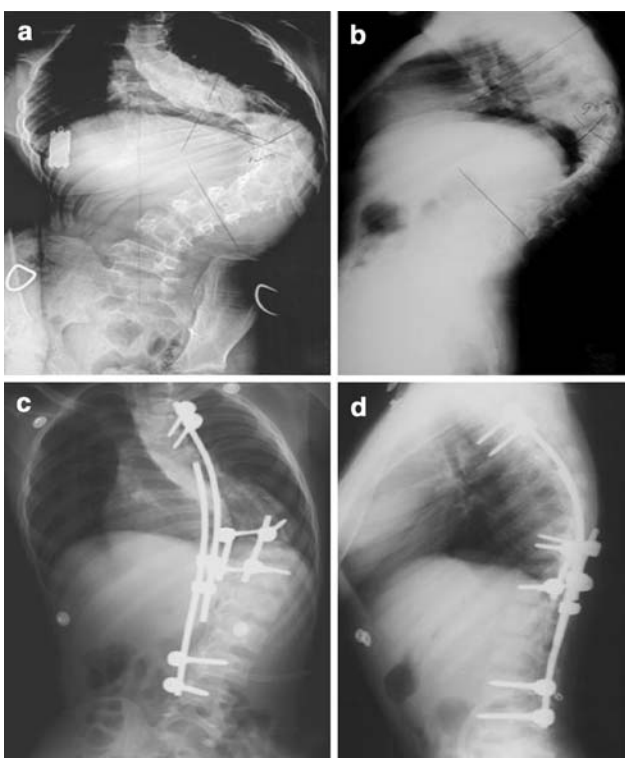

Fig. 1 Preoperative and postoperative radiographs of one case of complex severe scoliosis. The patient is a girl of 8 years old, using growth rods, osteotomy at the peak of the deformity (T11) to correct her kyphosis and scoliosis. **a** Preoperative posterior–anterior radiograph of a patient showing a scoliosis Cobb angle of 135°. **b** Preoperative lateral radiograph of the patient showing a kyphosis Cobb angle of 90°. **c** Postoperative posterior–anterior radiograph of the patient showing 40.7% correction. **d** Postoperative lateral radiograph of the patient showing 45.6% correction

All of the scoliosis and kyphosis deformities were corrected with pedicle screw system fixation. Postoperative plain film radiographs showed satisfactory correction in all cases (Fig. 1c, d), and comparison of postoperative and preoperative clinical appearance showed satisfactory results (Fig. 4). Postoperative CT images showed that all of the pedicle screws were in the pedicle tracts, with no cases of cortical wall perforation (Fig. 5).

Discussion

Correction of complex severe spinal deformity presents many challenges [4, 9, 22]. It is very important to evaluate the overall deformity before surgery to determine the operative plan and reduce the risk of major neurologic, vascular or other complications. Traditionally, plain film radiography, CT or MRI images were used to plan the surgical procedure, but these 2D images provided limited morphometric information about the deformity because of vertebral scoliosis, kyphosis, rotation and other factors [6, 12]. During surgery, discovery of an unexpected deformity often complicated the procedure.

Recently, various computer imaging programs have been used to visualize complex severe spinal malformation and plan the surgical procedure. Hedequist and Emans [10] assessed the efficacy of 3D CT reconstruction in identifying congenital vertebral anomalies. Operative findings showed that 3D reconstructions based on CT scans accurately predicted anterior and posterior vertebral anomalies in all 15 cases. Although plain film radiographs accurately predicted anterior anatomy, 11 of 12 posterior anomalies were not seen on plain film evaluation. Many authors have suggested that 3D reconstruction is required to obtain comprehensive information about complex severe spinal deformities, whereas CT 3D reconstruction can only be monitored on the CT working station from any direction and angle, but lacks tactile view.

Advances in computer technology have allowed scientists to acquire, store, manipulate and display more complex images. In 1989, the National Library of Medicine (NLM) began the Visible Human Project, which involved the use of computer technologies to build a prototype digital image library of data representing a complete normal adult human male and female [1, 2]. The Visible Human data set consisted of axial anatomical cryosections and corresponding CT and MR images of a human being.

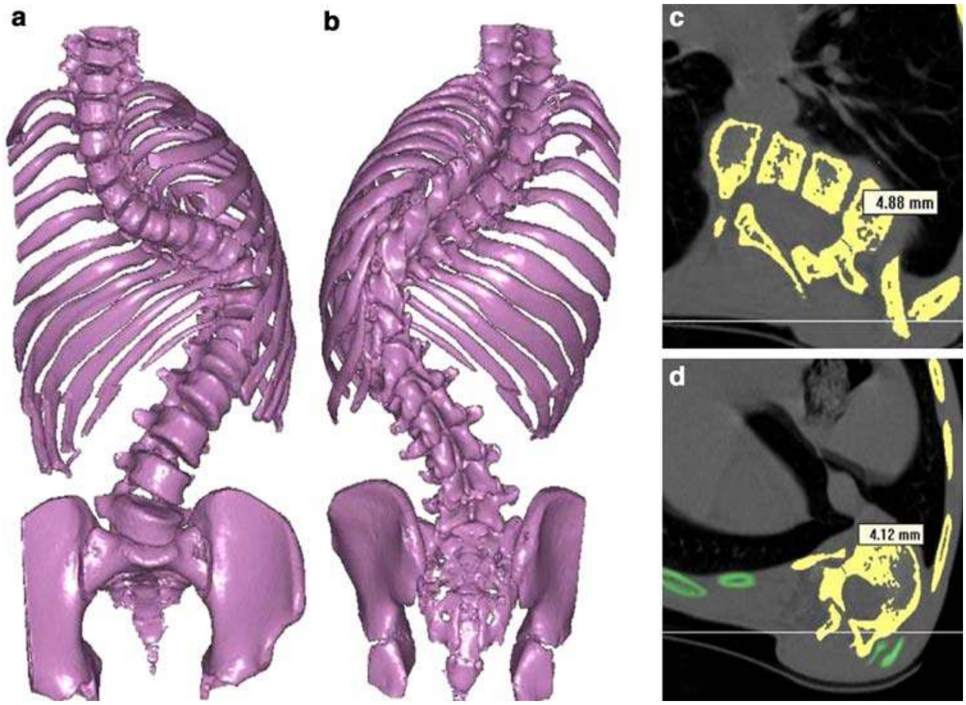

Fig. 2 Digital spinal three-dimensional reconstruction result based on the CT data set. **a**, **b** Spinal deformity can be viewed from any perspective. **c**, **d** The vertebral pedicle direction and diameter can be easily measured in plane from any angle on the personal computer with Mimics 6.3 software

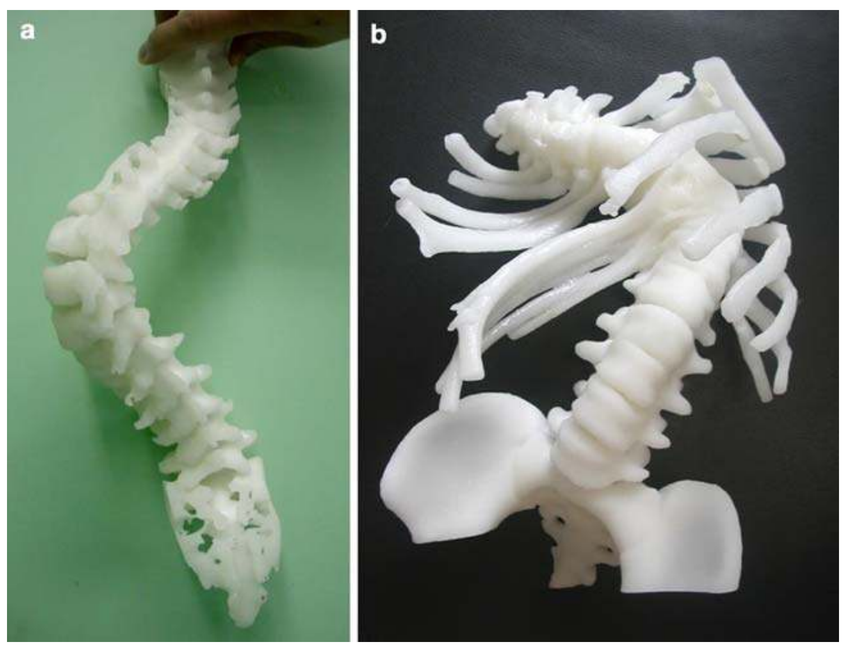

Fig. 3 Rapid prototyping templates of two cases of complex severe spinal deformity

The digital database is used to create 3D computer graphics, which support a wide range of educational, diagnostic, treatment planning and commercial uses. Many surgeons have used digital information to guide clinical treatment [14, 16, 18, 23]. Polly et al. [17] introduced computer-aided design/computer-aided manufacturing (CAD/CAM) to analyze spinal canal intrusion volumes for thoracic pedicle screws compared with thoracic laminar and pedicle hooks, which explains the safety of the clinical use of thoracic pedicle screws.

Similarly, segmented CT slice data can be used to construct and visualize a human digital spine. In this study, the slice DICOM format data set of each of the 16 affected spinal segments was obtained by CT scanning with a slice thickness of 1.25 mm and an interval of 1 mm. The deformed segment was easily reconstructed using a personal computer with Mimics 6.3 software, which allowed direct observation and measurement of the spinal deformity on a personal computer, not necessarily on the CT working station, facilitated the choice of

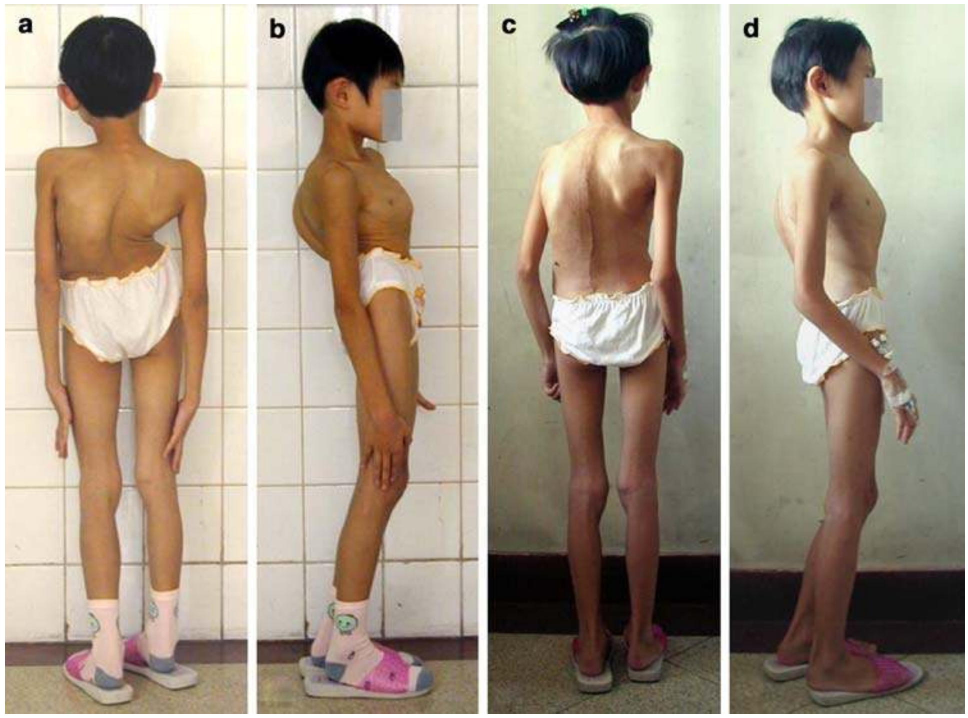

Fig. 4 Clinical appearance of the patient shown in Fig. 1. **a**, **b** Preoperative posterior and lateral views showing severe kyphoscoliosis. **c**, d Postoperative posterior and lateral views showing satisfactory correction

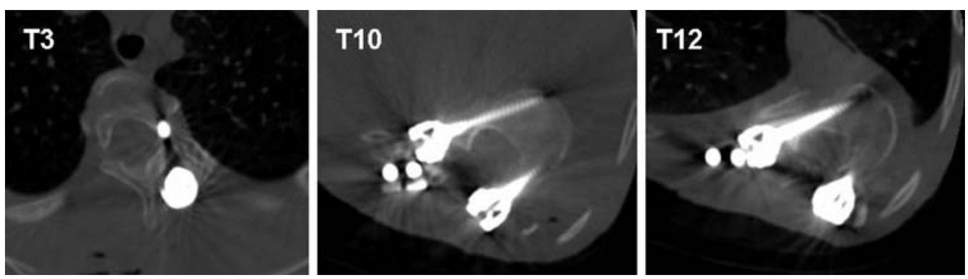

Fig. 5 Postoperative CT images showing the pedicle screws in the pedicle tract, without cortical wall perforation

internal-fixation instruments and increased the accuracy of pedicle screw placement.

Rapid prototyping and CAD/CAM techniques have been used in operative planning, surgical training, medical education, medical device fabrication and tissue engineering, especially for hard tissues such as bone [11, 18, 19]. Many rapid prototyping methods have been used to build models layer by layer. Wu et al. [24] described the fabrication of titanium dental crowns by means of laser measuring, numerical simulation and rapid prototype manufacture of wax patterns for the casting process. In the present study, an STL apparatus employed SLS technology to create a 3D spinal model, layer by layer, with laser-fused powder based on standard STL format data. An inverse projection was used to obtain the STL format file from CT scanning to fabricate the model with polystyrene resin powder. The result was an accurate tactile model that allowed direct visualization of the malformation from any perspective, facilitating surgical planning and the choice of internal-fixation instruments as a complementary.

Surgical correction of kyphoscoliosis deformities has been dramatically improved with pedicle screw use because of its higher pullout strength, increased curve correction and improved restoration of the sagittal profile. The use of pedicle screws, however, carries risks of major neurologic and vascular complications. Salako et al. [20] designed patient-specific surgical templates from an inverse projection of a CT scan to guide the drilling direction and angles for pedicle screw fixation. These templates were constructed in a CAD system using rapid prototyping. During the scoliosis operation, the surgeon placed the virtual template on the patient's vertebra until a perfect match was obtained, allowing optimal pedicle screw placement. In the present study, we used digital spinal reconstruction and rapid prototyping to allow accurate and direct visualization of the spinal deformity. During the pedicle screw insertion process, the template was placed beside the patient until a perfect match was found, guiding the direction and angle of the pedicle. The post-operative results showed good position of the pedicle screws with no complications. D'Urso et al. [5] used the same method to develop spinal stereotaxy with exact plastic copies of the spine manufactured using biomodeling technology. They regarded biomodel spinal stereotaxy as a simple and accurate technique with possible advantages over frameless stereotaxy.

This pilot study confirms that computer-designed polystyrene models are helpful in improving preoperative planning and treatment of complex severe spinal deformities. Compared to spinal radiography, CT, MRI and even 3D spinal reconstruction, the computer-designed polystyrene model served as a more tactile visual aid to confirm the positions of anatomical landmarks, helping the surgeon plan the operation and improve the accuracy of pedicle screw insertion. However, concerning the complex spinal deformity, huge amount of experiences has been accumulated in assessing spinal balance and flexibility through X-ray, while the model in this research is relatively new and cannot provide an accurate decision on spinal balance and flexibility. Therefore, this model could only be complementary to the X-ray method in deciding the surgical plan and fusion segments, providing more detailed deformity information and reducing complications. Occasionally, it was difficult to achieve an exact match between the model and the deformity, and further study of additional cases is needed to improve this technique.

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