Personalised modified osteotomy using computer-aided design—rapid prototyping to correct thoracic deformities

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Abstract The correction of severe thoracic deformities is challenging. However, the usual imaging modalities are not sufficient for performing the surgery. Our objective was to describe the procedure and results of posterior modified wedge osteotomy aided by the techniques of computer-aided design—rapid prototyping (CAD-RP) to correct thoracic deformities. Twenty-one patients with thoracic deformities (eight males; 13 females) formed the study group. All patients underwent computed tomography (CT) scanning and CAD-RP, and a model of thoracic deformities and navigation templates of pedicles were created for each patient and used to analyse the spinal deformities and serve as anatomical reference. Aided by these models, personalised modified wedge osteotomy combining the eggshell technique and posterior vertebral column resection was performed. Using CAD-RP improved the safety and accuracy of surgery and screw placement in the 21 patients in whom 41 vertebrae were removed and 216 pedicle screws were placed. The average operation time was 260 (200–420) min, with an average blood loss of

1,900 ml (range 800–3560 ml). The percentage of deformity correction was 56.3% (from 72.1° to 31.5°) in the coronal plane and 60.4% (from 81.6° to 32.3°) in the sagittal plane. No patient had serious complications or implant failure. Personalised single-stage posterior modified wedge osteotomy is an effective procedure for treating thoracic deformities. Using CAD-RP and the RP models have significant benefits for personalised surgical treatment of complex thoracic deformities.

Introduction

Correction of thoracic kyphosis or kyphoscoliosis is challenging for surgeons. To accomplish the operation safely and achieve the maximal correction effects, it is necessary to obtain as much information as possible about the malformation in each case. Although routine images can provide much morphometric information about the deformity [1, 2], they cannot fulfil the imaging requirements for accurate corrective surgery of complex deformities. Computer-aided design—rapid prototyping (CAD-RP) is an advanced technology that provides 3D reconstruction images and allows compilation of a physical model derived from computed tomographic (CT) image file data [3, 4]. The CAD-RP models can provide accurate visual representations of the complex deformities and are becoming an important adjunct for the surgical process [5–7]. Using CAD-RP, we performed personalised, modified osteotomy through the posterior approach and found that with the assistance of the RP model and navigation templates, efficacy and safety of osteotomy, as well as the accuracy of pedicle screw placement, were improved.

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Materials and methods

Twenty-one patients with thoracic kyphosis or kyphoscoliosis formed the study group [eight males and 13 females, average age 22.4 ± 11.6 (range 16–41) years]. There were ten post-traumatic thoracic kyphoses, six post-tubercular thoracic kyphoses and five congenital posterolateral hemi-vertebra thoracic kyphoscolioses. The angle of deformity was measured by projecting lines from the upper and lower border of the first healthy vertebra above and below the diseased area. Two to six vertebrae were involved in the fusion mass. Preoperative scoliosis Cobb angle was $72.1^\circ \pm 31.5^\circ$ (range 65° – 121°), and preoperative sagittal Cobb angle was $81.6^\circ \pm 31.3^\circ$ (74° – 117°) in cases with thoracic kyphosis. All patients were assessed with preoperative radiographs, magnetic resonance imaging (MRI) and CT.

CAD-RP of thoracic kyphoscoliosis

In all patients, the CT scanning field covered all deformity regions (Biograph 16 HR, Siemens, Germany) performed with a slice thickness of 1 mm and an interval of 1 mm. CT images were stored in Digital Imaging and Communications in Medicine (DICOM) 3.0 files and were downloaded to a personal computer. Using the Materialise TM interactive medical image control system 8.0 software (Materialise, Leuven, Belgium), a 3D model of the spine was reconstructed by setting a suitable threshold value, determining the procedure area from a 3D image calculation. The spinal deformity can be viewed from any direction, and information regarding the deformity can be obtained in detail. Extracting the anatomical information of thoracic vertebrae and combining the optimal implanting tract for the pedicle screw by searching the 3D digital reconstruction model, a digital navigation template of one vertebra could be made with two guide-hole locations. The 3D reconstruction was transferred to a stereolithography (STL) format file. An STL apparatus used selective laser sintering (SLS) technology (AFS-450, Beijing Long Yuan Automated Fabrication System, Beijing, China) to build an RP model layer by layer. The powder is laser-fused layer by layer based on the standard STL format files and accumulated to create a 3D model and template for implanting the pedicle screw, which has two guide holes. The length of hole was 2.5 cm and the internal diameter was 2 mm.

Personalised operation

Analysing the CAD-RP model of each patient, details of thoracic deformities were identified, such as shape, angle and diameter of the pedicle and the relationship of the

vertebral pedicle to ribs or other nearby osseous structures. Furthermore, the operation procedure was tested preoperatively on the model in each case. After being sterilised with epoxyethane preoperatively, the model was referred to during the actual procedure. All cases were performed under general anaesthesia. Patients were placed in a prone position with adequate padding for the chest and the pelvis (Fig. 1a). Particular care should be taken to avoid compression of the vena cava and the eyes. A modified procedure combining the eggshell technique and posterior vertebral column resection (PVCR) was adopted. According to the preoperative plan for each case, a midline or curved incision extending three or four vertebrae above and below the involved segments was performed, and the spine was exposed. Using the model as reference, the target vertebrae and the entry point, length and angle of the pedicle screws could be assured. Through the navigation templates, the pedicle screws were carefully placed. The ribs at the involved level were transected 3–4 cm lateral to the costotransverse joint. The rib heads and the transverse process were carefully excised. Using the reference RP model, the lamina and zygapophysis of target vertebrae were excised, and a temporary rod that contoured to accommodate the deformity was applied to maintain spinal stability while performing resection of the anterior column. From the stump of the apical vertebra pedicle, the vertebral cancellous bone was carefully removed using curette and high-speed burr (Fig. 1d). Entry was then enlarged both cephalically and caudally to the the upper and lower end plates of the involved vertebra, and the intervertebral space was removed, retaining the posterior vertebral cortex. The anterior and lateral residual thinned cortex were removed with a curette or rongeur. A second temporary rod was then attached to the screws on the opposite side. The initial rod was removed and the same decompression procedure repeated on the other side. At the end of decompression, the posterior vertebral cortex, which had been adequately thinned out with a diamond-tip burr, was then removed with a special strike tool.

The correction was performed after the osteotomy was accomplished. The gap in the anterior column was measured and a vertebral spacer was implanted, such as a titanium mesh cylinder with autograft inside, polyetheretherketone (PEEK) cage with autograft inside or a tricortical iliac crest graft. Chip grafts obtained from the osteotomy were inserted into the residual intervertebral spaces. By carefully replacing and rotating the differently contoured rods, the spinal deformity was corrected step by step, after which the rods were firmly secured. The entire procedure should be performed slowly to avoid suddenly kinking and stretching the spinal cord. Closed suction drain was inserted, and the incision was closed layer by layer. Spinal cord evoked potential monitoring and wake-up test were performed to ensure neurological function during

Fig. 1 A 23-year-old woman who presented with post-tubercular thoracic kyphosis. The preoperative kyphosis Cobb angle is 100° and postoperative Cobb angle 32° . **a** Preoperative image. **b–e** Modified osteotomy procedure was carried out to resect vertebrae of T6–T10, with posterior pedicle screw fixation, vertebrae compression and fusion with titanium mesh cylinder with autograft inside. **f** Postoperative image. **g, h** Preoperative radiographs. **i, j** Postoperative radiographs

the operation. All patients were treated with an orthosis for three months and were checked with postoperative radiographs to assess the result of osteotomy and the accuracy of the CAD-RP model.

Results

Three-dimensional digital spinal models (Fig. 2) using CAD-RP technology based on CT data were performed in all cases. After that, the model of each case could be clearly observed from any direction and angle on both computers and the reconstructed models, to attain detailed information about the thoracic deformities, such as the bulk of involved vertebrae, the degree of destruction or residual vertebrae, the direction and angle of vertebral rotation and the direction, diameter and depth of each pedicle (Figs. 2 and

3). Because the model was exactly the same size as the actual spinal deformity, it provided a tactile anatomical representation, which allowed individualised operation planning for each case and the choice of the appropriate internal-fixation instruments. During surgery, the sterilised model, matched with the exposed spinal deformity, provided direct guidance to determine the range of osteotomy. Aided by the model and the navigation template (Fig. 2), we could easily choose the optimal entry point, drilling direction, angle and length of the pedicle.

In all cases, correction was performed with pedicle-screw fixation aided by the CAD-RP technique. Average operation time was 260 (200–420) min, with average blood loss of 1,900 (800–3,560) ml. Deformity correction ratio was 56.3% in the coronal plane postoperatively (from 72.1° to 31.5°). The correction ratio of kyphosis was 60.4% (from 81.6° to 32.3°). In all, 41 vertebrae were removed and 216

Fig. 2 a–d Three-dimensional digital reconstruction of spinal deformity based on computed tomographic data set. On the model, the deformity can be viewed from any perspective. **e, g, h** Rapid-prototyping (RP) model of three severe thoracic kyphoscoliosis and kyphosis deformities; **f** sterilised RP model was placed beside the incision to match with the exposed spinal deformity, and the pedicle screws were implanted by reference to the navigation template

pedicle screws placed without serious complications or internal fixation failure. In one patient, a decrease in the amplitude of spinal cord evoked potentials occurred during rod rotation to the maximal extent. We reduced the extent of correction immediately and stopped the operation until amplitude recovery and performed the wake-up test before closing the incision. After the operation, no neurological deficit was detected. Postoperative CT images showed that all pedicle screws were in the pedicle tracts (Fig. 3e, f). The correction effects were satisfactory in all cases, as shown by postoperative plain-film radiographs with compared with preoperative ones (Fig. 1, g–j).

Discussion

Corrective surgery for severe thoracic kyphoscoliosis is one of the most complex operations in orthopaedics. In this study, we achieved ideal results in 21 cases of severe thoracic deformities by using personalised, modified, wedge osteotomy through posterior-only approach aided by CAD-RP technology. To achieve ideal correction of complex thoracic deformities, it is very important to evaluate the deformity accurately before surgery, so that the surgeon can precisely plan the operation and reduce the risk of neurological and vascular injuries or other compli-

cations. Traditional imaging methods, such as radiography, MRI and 2D and 3D CT images are widely used in orthopaedics, but these images alone cannot provide adequate and accurate information about complex deformities [8, 9]. Recently, the technique of CAD-RP, based on newly developed computer technologies with digitised 3D reconstruction and emulation, has been used to visualise complex spinal malformation to help surgeons plan and imitate the surgical procedure [9, 10]. With our experience with 21 cases of operations using CAD-RP for thoracic kyphoscoliosis, we found that CAD-RP is particularly beneficial in two ways: Firstly, the model can be visualised from any perspective and direction so surgeons have intuitive understanding about the deformities, which greatly helps planning the operation, for example, formulating the suitable modality of osteotomy; determining the target vertebrae, location and range of resection; and the length of posterior column closing and anterior column opening. Secondly, the models act as intra-operative references, which provide direct guidance for screw placements.

Screw placement in the thoracic vertebral pedicle can be a challenge, as the spine exhibits various degrees of translation, rotation and angulation. Many methods have been used to place the pedicle screws for thoracic vertebrae. Commonly, the implantation is primarily based on conven-

Fig. 3 a–d Direction and angle of vertebral rotation and direction, diameter and depth of each pedicle. e, f Postoperative computed tomography images showing pedicle screws in the pedicle tract

tional imaging data, the intraoperative bony anatomical landmark of vertebrae and by feel with the surgeon's hand. However, these methods have certain limitations and require a surgeon with extensive experience in spine surgery. Kim et al. [11] found that the accuracy of pedicle-screw implantation ranged from 69.4% to 93.8% and the rate of perforation of pedicle walls ranged from 6.2% to 30.6%. For each patient with thoracic scoliosis or kyphosis, due to the malformation of the pedicle and the abnormality of posterior bony anatomical landmarks, the placement of pedicle screws is more difficult and challenging. To improve accuracy and reduce complications, the RP model was used in this study to analyse specific details of the malformation of each pedicle. The optimal corridor of screw placement was designed, and a navigation template was created using the CAD-RP for each pedicle [5, 6, 9]. Aided by intraoperative reference to the navigation templates and the RP model, 216 suitable screws were

implanted in the pedicle safely without complications, pedicle-wall perforations or neurovascular injuries.

With assistance of the CAD-RP, we performed modified osteotomies using the posterior-only approach, which integrates advantages of both closing and opening wedge osteotomy and the eggshell technique while avoiding their shortcomings. The closing and opening wedge osteotomy described by Kawahara et al. [12] is essentially the same technique as posterior vertebral column resection described by Suk et al., which provides tremendous potential for deformity correction and appears to be the most powerful posterior osteotomy method. However, it carries a significant risk of complications, including potentially permanent neurological lesions [13–16]. Suk et al. found a 34.3% overall rate of complications, a 17.1% rate of neurological complications and a 7.1% fixation failure in a series of 70 patients [13]. Lenke et al. reported a similar 40% overall rate of complications as well as an 11.4% rate of neurological complications in a study of children [17]. According to recent studies, the eggshell technique can achieved a degree of kyphosis correction ranging from 26.2° to 40.1°, with an average of 32°. However, the degree of correction was not great enough, especially for severe thoracic deformities. Moreover, a rather high complication rate was also shown [18–23]. Bridwell et al. found an 11.1% rate of neurological deficits and a 2.8% rate of permanent deficits [16, 24].

To perform surgery safely and achieve optimal correction, we combined the PVCRC and eggshell techniques aided by CAD-RP to design a modified technique for treating severe thoracic deformity. The key steps of this technique are summarised as follows. Firstly, posterior structures were removed and the medial wall of pedicle was exposed. Then, the eggshell technique was performed to decancellate through the pedicle stump. This is different from the conventional eggshell technique [22] and the modified vertebral column resection (MVCRC) technique reported by Wang et al. [25]. Using our model, the spinal cord and nerve roots can be visualised and protected to avoid injury. During decancellation, a thin wall of cortical bone at the lateral and posterior parts of the vertebra was reserved. The entry was further enlarged both cephalad and caudad from the apical vertebra to expose the upper and lower intervertebral spaces of the target vertebrae according to preoperative plan and intraoperative RP model reference. These steps are both different from the PVCRC technique.

In summary, this study confirms that CAD-RP is beneficial for preoperative planning and intraoperative reference and allows satisfactory correction of complex thoracic deformities. The RP model, serving as a tactile visual aid and anatomical reference, can help surgeons perform the personalised modified osteotomy more safely and effectively. In addition, the RP model is helpful as a

communication tool, providing patients with a better appreciation of their condition, details of the planned surgical procedure and the subsequent risks involved while facilitating communication within the surgical team. The navigation template can improve the accuracy of pedicle-screw insertion. However, as a relatively new technique, CAD-RP cannot provide an accurate decision regarding spinal balance and flexibility, nor can it provide accurate analysis of neurovascular structures adjacent to the deformity. Occasionally, it was difficult to achieve an exact match between the model and the deformity; therefore, further study is needed to improve this technique.

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