Original Article

Application of three-dimensional reconstruction technology combined with three-dimensional printing in the treatment of pectus excavatum

Yibo Shan[1,2,3,4], Guiping Yu[4], Yi Lu[1,2,3], Hao Kong[1,2,3], Xuewei Jiang[4], Zhiming Shen[1,2,3], Fei Sun[1,2,3], Hongcan Shi[1,2,3]

[1]Clinical Medical College, Yangzhou University, Yangzhou 225000, China, [2]Institute of Translational Medicine, Medical College, Yangzhou University, Yangzhou 225000, China, [3]Jiangsu Key Laboratory of Integrated Traditional Chinese and Western Medicine for Prevention and Treatment of Senile Diseases, Yangzhou University, Yangzhou 225000, China, [4]Department of Thoracic Surgery, Jiangyin People's Hospital, Jiangyin 214400, China

Address for correspondence:
Dr. Hongcan Shi, Medical College, Yangzhou University, No.136 Jiang Yang Mid Road, Yangzhou 225000, China.
E-mail: shihongcan@yzu.edu.cn

Submission: 08-11-2021
Accepted: 18-01-2022
Published: 09-07-2022

Abstract:

OBJECTIVES: To explore the clinical value of three-dimensional (3D) reconstruction technology combined with 3D printing in the treatment of pectus excavatum (PE).

METHODS: The clinical data of 10 patients with PE in our department from June 2018 to December 2020 were analyzed retrospectively. All patients underwent thin-layer computed tomography examination before the operation, and then 3D reconstruction was performed with Mimics 20.0 software. The radian and curvature of the pectus bar were designed according to the reconstructed images. Afterward, the images were imported into the light-curing 3D printer in STL format for slice printing. Hence that the personalized operation scheme, including the size of the pectus bar and the surgical approach, can be made according to the 3D printed model. The thoracoscopic-assisted Nuss operation was completed by bilateral incisions. The operation time, intraoperative blood loss, and postoperative hospitalization were counted and analyzed. The satisfaction of the surgery was evaluated according to the Haller index and the most posterior sternal compression sternovertebral distance.

RESULTS: The surgeries were successfully completed in 10 patients without a transfer to open procedure. The average operation time was (56 ± 8.76) min, the intraoperative blood loss was (23.5 ± 11.07) mL, and the postoperative hospitalization was (7.2 ± 0.92) d. There were no serious complications or death during the perioperative period. Compared with the data before the operation, the most posterior sternal compression sternovertebral distance was larger, and the Haller index was lower, the differences were statistically significant ($P < 0.05$).

CONCLUSIONS: 3D reconstruction technology combined with 3D printing, which can be used before operation, contributes to the operator performing thoracoscopic-assisted Nuss operation safely and effectively, which has productive clinical application value for the treatment of pectus excavatum.

Keywords:

Nuss, pectus excavatum, thoracoscopic-assisted surgery, three-dimensional printing, three-dimensional reconstruction

Access this article online

Quick Response Code:

Website:
www.thoracicmedicine.org

DOI:
10.4103/atm.atm_506_21

Pectus excavatum (PE) is the most common congenital chest wall deformity, which is characterized by posterior depression of sternum and lower costal cartilages resulting in a "funnel chest."[1-3] It is usually caused by congenital developmental anomaly; however, the specific causes are not clear. The incidence rate of PE is about 0.1%–0.3%, whereas males are affected three to four times more often than females. Statistics also show that the incidence rate in Asia is higher than that in Europe and America. When it causes cardiopulmonary complications that lead to chest pain, shortness of breath, dyspnea on exertion,

This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 License, which allows others to remix, tweak, and build upon the work non-commercially, as long as appropriate credit is given and the new creations are licensed under the identical terms.

For reprints contact: WKHLRPMedknow_reprints@wolterskluwer.com

How to cite this article: Shan Y, Yu G, Lu Y, Kong H, Jiang X, Shen Z, *et al*. Application of three-dimensional reconstruction technology combined with three-dimensional printing in the treatment of pectus excavatum. Ann Thorac Med 2022;17:173-9.

and exercise intolerance, it usually needs surgical correction.[4] Long years ago, the surgical treatment of PE was mainly in open operation, which needed to cut open the sternum and other bone structures with great trauma. It was not until May 1997 that Dr. Donald Nuss implemented the new minimally invasive surgery for the first time in the American Pediatric Surgery Association that a new chapter in the invasive surgical treatment of PE was opened.[5] With the continuous exploration, development and improvement of minimally invasive technology and the continuous maturity of thoracoscopic technology, thoracoscopic-assisted Nuss surgery has also become the mainstream surgical treatment of PE. The crux of the operation is that experienced surgeons need to select the most appropriate intercostal orthopedic plate and adjust the radian and curvature of the pectus bar during the operation. The difficulty of the surgery for the operator is positively correlated with the severity of the chest wall deformity. The size, length, and curvature of the pectus bar needed during the operation are important factors to the success of the surgery and postoperative satisfaction.[6] Therefore, there were several limitations for the traditional Nuss procedure. Although advanced radiological technology, such as computed tomography (CT) and computer three-dimensional (3D) visualization, has been utilized for the evaluation of chest wall deformity, it was difficult to evaluate the repair efficacy of Nuss surgery. Moreover, to assess the size and curvature of the pectus bar accurately was still difficult because of the mobility of the thorax after surgery, which might cause the displacement and looseness of the bar. 3D reconstruction and 3D printing technology are widely used in preoperative planning and formulation to overcome these weaknesses.[7] 3D reconstruction and 3D printing technology, which have been employed in our department to draw up the preoperative protocol, combined with thoracoscopic-assisted Nuss surgery, which was accomplished with bilateral incisions, has achieved favorable operation effect and postoperative satisfaction.

Methods

General information

A total of 10 patients with PE needing surgery treatment in our department from June 2018 to December 2020 were retrospectively analyzed, including 7 males and 3 females. The youngest was 9 years old and the oldest was 17 years old, with an average age of 12.6 ± 2.32 years. All patients underwent blood routine examination, thin-layer CT, cardiac ultrasound, pulmonary function, and electrocardiogram before operation to evaluate the severity of the disease. According to CT images, the maximum internal transverse diameter of the thorax at the deepest depression and the most posterior sternal compression sternovertebral distance were measured, and then the Haller index was calculated (ratio of the transverse diameter of the chest to the anteroposterior distance, as measured from the anterior border of the vertebral body to the posterior border of the sternum), with an average of 4.13 ± 0.31.

Inclusion and exclusion criteria

Inclusion criteria

(1) PE was diagnosed by clinical symptoms and imaging, including X-ray or CT examination; (2) PE was caused by congenital dysplasia;[8] (3) no psychiatric symptoms and communication barriers; (4) patients had adequate cardiopulmonary function to tolerate the operation; (5) Haller index >3.2;[4,8](6) this study was approved by the Ethics Committee (Ethics approval number: 2018-012). All patients volunteered to participate in the study and signed informed consent forms.

Exclusion criteria

(1) Patients had other congenital thoracic deformities; (2) patients had congenital cardiovascular and cerebrovascular diseases, severe liver and kidney dysfunction, malignant tumors, or other such diseases; (3) patients had coagulation defects; (4) patients were seriously allergic to the plastic steel plate.[8]

Three-dimensional reconstruction and three-dimensional printing

Thin-layer CT scanning with a slice thickness of 1 mm was applied before operation. The imaging data were imported into Mimics Medical 20.0 software in DICOM format. The Split Mask function in the software can accurately extract the cortical bone in the sternum. At the same time, the low-density fibrous cartilage in the sternum was not selected. Then, the image was edited by using the tools provided in the Multiple Slice Edit function to remove useless tissues or organs and reduce the interference to the model layer by layer. These two steps were cumbersome, while they could confirm the structural accuracy. After that, the sternum could be reconstructed and the digital model was smoothed by Geomagic Wrap software to compensate for coarseness caused by the segmentation making sure that it would not change the characteristics of the thorax structures, as shown in Figures 1 and 2.

The reconstructed images were exported as STL format to the light-curing 3D printer for slice printing (supported by Nanjing Medprint Medical Technology Co., Ltd.). The thoracic model was printed by stereolithography apparatus, which is a technology with high precision and fast speed of 3D printing technology. This technology takes photosensitive resin as raw material and relies on photopolymerization. The ultraviolet laser was under the control of the computer and liquid resin was scanned according to the contour of each layered section of the predetermined model, so that a thin layer section of the model could be formed. At last, a 3D printed (3DP) thoracic model was obtained through mechanically stacking layer by layer, as shown in Figure 3. According to the 3DP PE model, the size of the pectus bar could be determined, the surgical approach and trajectories of the pectus bar could be confirmed, the personalized surgical scheme could be planned and the operation could be demonstrated for family members of patients, as shown in Figure 4.

Surgical methods

The patients received endotracheal intubation through a single lumen, routine anesthesia, and muscle relaxation. All the patients were given antibiotics 30 min before the operation. When the general anesthesia produced the effect, the patient was laid in the supine position and the operation field was disinfected. According to the preoperative 3D reconstruction and 3DP model, the deepest level of the PE was positioned. A skin incision of approximately 1.5–2 cm was made vertical to the longitudinal axis near each midaxillary line, and a submuscular tunnel was created along each incision to the anterior chest wall until the intersection of the funnel edge and the predesigned intercostal space.

A perforating guider was placed into the tunnel via the right high-level incision under the guidance of the thoracoscope. The pectus bar whose radian and curvature have been shaped based on the preoperative reconstruction image was entered into the chest cavity through the predesigned intercostal space, carefully moved through the clearance between the anterior mediastinum and sternum while closely adhering to the posterior sternum, and moved out of the chest cavity at the symmetric intercostal space on the left side. The position of the pectus bar was adjusted to make sure that the thorax is lifted and well-shaped. A stabilizer was set at the right end, the pectus bar was combined with steel wire, and then the pectus bar was reinforced on the rib. Gas in the chest cavity was discharged and the lungs were inflated. There was no active bleeding through the observation of thoracoscopy and the bilateral incisions were sutured layer by layer. Routine placement of the chest tube was not needed. The operation time and intraoperative blood loss were recorded. The patients were followed up at 1-month postoperation and 6-month postoperation to calculate the Haller index again.

Statistical analysis

All data were expressed as ($\bar{X}\pm s$) and analyzed using SPSS 22.0 (IBM, Armonk, N. Y, USA). A *t*-test was used to compare two groups. $P < 0.05$ was considered statistically significant.

Results

1. All the surgeries were successfully completed without conversion to thoracotomy. The average operation

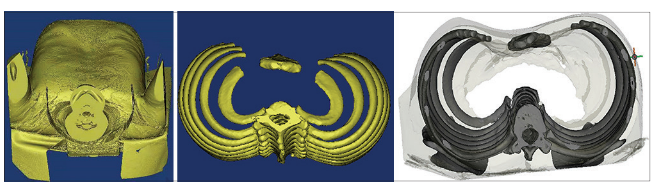

Figure 1: Sternal reconstruction

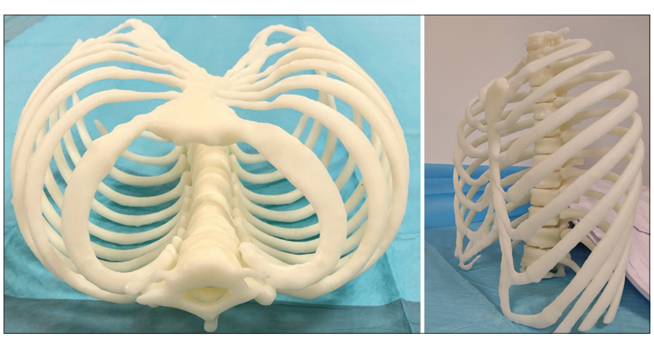

Figure 3: The pectus excavatum of three-dimensional printed thoracic model (the ratio was 1:1)

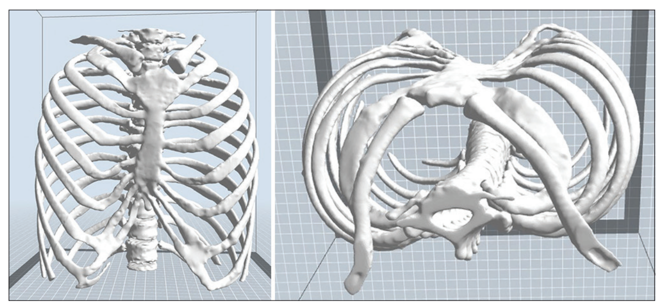

Figure 2: Before exporting the data to the three-dimensional printer, the digital model was smoothed

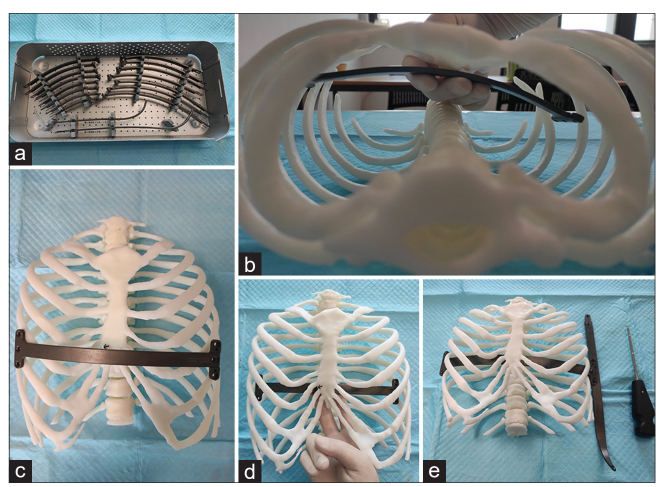

Figure 4: Application of three-dimensional printed Pectus excavatum model before thoracoscopic-assisted NUSS surgery. (a) Different sizes of the pectus bar; (b and c) to determine the size of the pectus bar; (d) to confirm the trajectory of the pectus bar; (e) to demonstrate the surgical procedure

time was (56 ± 8.76) min, the intraoperative blood loss was (23.5 ± 11.07) mL, and the postoperative hospitalization was (7.2 ± 0.92) d, as shown in Table 1. There were no serious complications or death during the perioperative period. The postoperative X-ray examination confirmed that there was no depression in the sternum and no displacement of the orthopedic plate. It's obvious to show the symmetrical appearance of the thorax with good elasticity and extension, as shown in Figures 5-8. The last but not the least, the patients and their family members were satisfied with the surgical effect

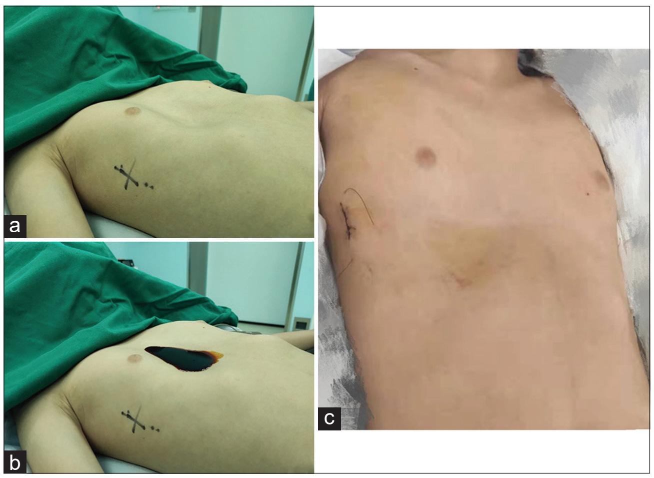

Figure 5: Comparison of patients' appearance during perioperative period. (a and b) The appearance before surgery; (c) The appearance at the 7-day postoperation (discharge day). (This little girl was 13 years old when she came to our department. She complained that she had found the pectus excavatum for more than 3 years. Thoracoscopic-assisted Nuss operation was completed on July 15, 2020)

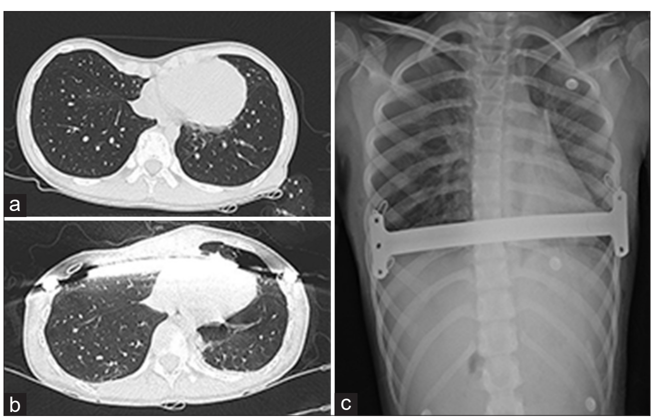

Figure 7: Imaging comparison of patients during perioperative period. (a) Thin-layer computed tomography image before surgery; (b) thin-layer computed tomography image after surgery, the highlight is the pectus bar; (c) there was no depression in the sternum and no displacement of the orthopedic plate after surgery from the X-ray image

2. Compared with the data before the operation, the most posterior sternal compression sternovertebral distance was larger, and the Haller index was lower, the differences were statistically significant ($P < 0.05$), as shown in Table 2.

Discussion

Chest wall deformities are structural abnormalities of the chest, among which PE is the most common one. Its clinical manifestation is that the sternum and its accompanying costal cartilage are sunken to the spine with the funnel-shaped appearance, just as its name implies. PE is caused by the excessive growth of the costal cartilage, resulting in a concave anterior chest wall.[9] About 90% of children were shown the symptoms within 1 year of birth, and the symptoms gradually worsened

Figure 6: Anatomical position at 1-month postoperation

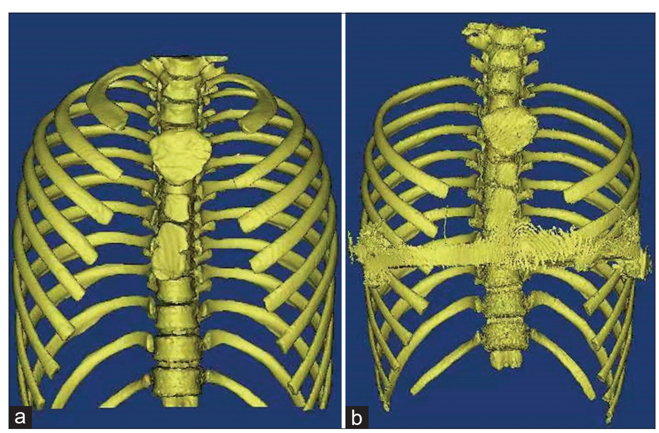

Figure 8: Validation of three-dimensional reconstructed images. (a): The image before surgery; (b) The image after surgery, and the pectus bar was penetrated from the fifth intercostal space

Table 1: General information and Surgical data of the patients ($\bar{X}$±S)

Gender		Age (years old)	Operation time (min)	Intraoperative blood loss (mL)	Postoperative hospitalization (d)
Male	Female				
7	3	12.6±2.32	56±8.76	23.5±11.07	7.2±0.92

Table 2: Comparison of indexes during the perioperative period (X̄±S)

Period	Cases	Haller index	The most posterior sternal compression sternovertebral distance (mm)
Preoperation	10	4.13±0.31	52.46±1.43
1-month postoperation	10	3.19±0.13*	60.72±2.25*
6-month postoperation	10	2.78±0.13*	64.58±1.98*

*Compared with preoperation, $P<0.05$

with age.[10] The pathogeny of congenital PE is complex and cannot be completely expounded at present. Most scholars believe that it may be related to uncoordinated rib growth, sternal development disorder, abnormal diaphragm development, abnormal bone alkaline phosphatase and genetic factors.[11] According to the Haller index, PE can be divided into different severity levels. Haller index ≤3.2 is the mild level, 3.2 <Haller index <3.5 is the moderate level, and 3.6 <Haller index <6.0 is the severe level. As we all know, the degree of harms to children's cardiopulmonary function is positively correlated with the degree of depression.[12] If the orthopedic treatment is not timely, it can lead to the hunchback and poor growth, further to the change of chest space and volume, which would endanger the heart, the lung and other organs, causing serious damage to the children's physical and mental health and increasing the family burden.

Surgery is an effective method for the treatment of PE, which can not only repair the abnormal morphology but also prevent further damage to cardiopulmonary functions caused by the compression of sternal depression.[13] There were several surgical methods previously, including sternal turnover, sternal uplift (Ravitch) and its modified methods. In recent years, nonoperative vacuum bell for PE and bracing for pectus carinatum have been applied with satisfactory results.[11,12] The advent of minimally invasive Nuss surgery was wildly recognized as the revolution of PE surgery. It has become the mainstream surgical method for the treatment of PE because of its advantages of lower mortality, less surgical trauma, lower complication rates, shorter operation time, less operative blood loss, shorter hospitalization, and faster recovery.[14,15] Children are still in the stage of growth, and their bone structures are not yet mature, which have certain compliance and greater plasticity. As a consequence, the depressed thorax can achieve the effect of correction and remodeling under the long-term influence of external force.[16] Based on this theory, Nuss innovatively put the steel plate which has shaped according to the thoracic depression into the thorax, nearing to the sternum, so that the depressed sternum and costal cartilage can raise up the thorax to achieve the purpose of shaping through the support of the orthopedic steel plate.[17] The Nuss procedure was suggested in the pediatric population, but the patients' selection in adulthood should be decided cautiously for the association with higher surgical risk, more postoperative complications, and longer operation time. At the outset, the preferable age was infancy because of the plasticity of the infant's sternum. With the depth of research, it is said that surgical treatment is recommended in adolescence when the sternum is closer to skeletal maturity but also remains moldable to a certain degree.[18,19]

When Pro. Jacobaeus in Sweden utilized the endoscope with the light source to insert into the patient's chest for the first time, a new era of thoracoscopic surgery was opened. Furthermore, the diagnosis mode and surgical methods of thoracic diseases have changed fundamentally in the following more than 100 years.[20] There is no doubt that thoracoscopy also affected the minimally invasive Nuss operation which has obvious better early effects. Some scholars believe that the depression of PE can cause the left displacement of mediastinum. As a result, the assistance of thoracoscopy inserting from the right side can broaden the surgical field of vision, improve surgical safety and enhance the surgical effect. Some scholars have also proposed that the operation can be completed through the xiphoid process approach, the left approach or the bilateral approach.[21] The mobility of thorax during breathing makes it different from other organs. The location of ribs, centrums, and sternum would move after the orthopedics of the thorax. However, regardless of the approach, the depression sternum was supported by the pectus bar, which was loaded against the ribs. Therefore, the choice of substernal force point in surgery can significantly influence the repair efficacy. As a coin has two sides, for some patients with asymmetric or severe PE, it became more difficult to make sure the optimal substernal force point. It is worth noting that the successful implementation of PE surgery highly depends on the experience of the surgeon, which leads to the uncertainty of repair efficacy. To sum up, the selection of substernal force points and trajectories of the pectus bar has become especially important.[22,23]

With the continuous research and updating of 3D reconstruction and 3D printing technology, they spread more and more wildly and have been already applied as an alternative strategy for surgical decision-making. The technology is a favorable tool for specific description and stereoscopic display of anatomical and morphological features of organs, which provides great assistance for surgeons to evaluate surgical risks, plan surgical approaches and simulate surgical operations.[24] Three-dimensional reconstruction technology has been widely used in general surgery and orthopedics.[25-27] 3D printing, also known as additive manufacturing and rapid printing, has the advantages of fast construction, high precision, and personalized production, which speed up its application in the medical field, especially in surgical planning and operation.[28] 3D printing technology mainly includes fused deposition modeling, powder bed fusion, and stereolithography appearance (SLA).[29] In our study, the SLA technology was used without producing thermal diffusion and thermal deformation. In addition, the chain reaction can be accurately controlled to ensure that the polymerization reaction does not occur outside the laser point. On account of this, SLA technology is equipped with high machining precision and satisfied surface quality.

In our study, 10 patients with PE treated in our department from June 2018 to December 2020 were retrospectively analyzed. The Haller index measured before operation indicated a severe level of PE, with an average index of 4.13 ± 0.31. The depressed sternum and costal cartilage were displayed from different angles by 3D reconstruction technology. Furthermore, 3D-printed thoracic models allowed us to clearly identify the dimensions of the deformities and the exact intercostal space of the trajectories of the pectus bar, which is shaped according to the symmetry and severity of the chest deformity. 3D printed models also can help us to find the optimal substernal force point by penetrating the pectus bar in these models before surgery and make sure the appropriate intercostal space, making the surgical scheme more individualized and precise. At the same time, the 3D printed models can also be utilized for preoperative conversation by the surgical simulation to help patients and their families understand the operation process and risks more clearly. Thoracoscopic-assisted Nuss operation adopts double incisions by right approach with satisfied operation field and low surgical risk. All the surgeries were successfully completed without conversion to thoracotomy. The average operation time was (56 ± 8.76) min, the intraoperative bleeding was (23.5 ± 11.07) mL and the postoperative hospital stay was (7.2 ± 0.92) d. There were no serious complications and no death cases during the perioperative period. During the follow-up after the operation, the patients and their family members were satisfied with the surgical effect while there was no depression in the sternum and no displacement or looseness of the orthopedic plate. Compared with the data before the operation, the most posterior sternal compression sternovertebral distance was larger, and the Haller index was lower, the differences were statistically significant ($P < 0.05$), which provided a favorable space for the development and maturation of the heart and lung.

Conclusions

3D reconstruction and 3D printing technology combined with thoracoscopic-assisted Nuss surgery is conducive to improve the surgical efficacy with precious application value for the treatment of patients with PE, which is worthy of further promotion in clinical practice. However, we acknowledge several limitations of this study, including the small sample size of 10 patients, which needs more data to support the study. Besides, as mentioned in this paper, the pectus bar used in the operation was still the traditional orthopedic steel plate, which needs manual bending and correction before operation. Even if there are more accurate data after reconstruction, it still can not perfectly fit the patient's own configuration. Therefore, our research group will print the precise prebending of the pectus bar by 3D printing technology. In addition, it still takes high cost, and how to reasonably solve the cost problem needs to be further discussed in clinical practice. We firmly believe that as the 3D printing technology becomes widely accepted, the cost will most likely decrease. In the future, this technology or computer-assisted design systems for medical applications will continue to expand.

Acknowledgments
The authors would like to thank the National Natural Science Foundation of China (General Program 81770018, 82070020).

Financial support and sponsorship
This study was supported by the National Natural Science Foundation of China (General Program 81770018, 82070020).

Conflicts of interest
There are no conflicts of interest.

References

1. Brochhausen C, Turial S, Müller FK, Schmitt VH, Coerdt W, Wihlm JM, *et al*. Pectus excavatum: History, hypotheses and treatment options. Interact Cardiovasc Thorac Surg 2012;14:801-6.
2. Sharma G, Carter YM. Pectus excavatum. In: StatPearls. Treasure Island (FL): StatPearls Publishing; 2021.
3. Rha EY, Kim JH, Yoo G, Ahn S, Lee J, Jeong JY. Changes in thoracic cavity dimensions of pectus excavatum patients following Nuss procedure. J Thorac Dis 2018;10:4255-61.
4. Beltsios ET, Mitsos SL, Panagiotopoulos NT. Pectus excavatum and scoliosis: A review about the patient's surgical management. Gen Thorac Cardiovasc Surg 2020;68:1225-33.
5. Notrica DM. Modifications to the Nuss procedure for pectus excavatum repair: A 20-year review. Semin Pediatr Surg 2018;27:133-50.
6. Vilaça JL, Rodrigues PL, Soares TR, Fonseca JC, Pinho AC, Henriques-Coelho T, *et al*. Automatic prebent customized prosthesis for pectus excavatum minimally invasive surgery correction. Surg Innov 2014;21:290-6.
7. Ni ZK, Lin D, Wang ZQ, Jin HM, Li XW, Li Y, *et al*. Precision

liver resection: Three-dimensional reconstruction combined with fluorescence laparoscopic imaging. Surg Innov 2021;28:71-8.
8. Section of Cardiothoracic Surgery; Branch of Pediatric Surgery; Chinese Medical Association. National consensus on surgery for pectus excavatum in China. Chin J Pediatr Surg 2020;41:7-12.
9. Kondo S, Takagi D, Osaga S, Okuda K, Nakanishi R. The costochondral length in patients with pectus excavatum is longer than that of the normal thorax. Pediatr Surg Int 2020;36:305-16.
10. Tepper OM, Rudy HL, Lefkowitz A, Weimer KA, Marks SM, Stern CS, *et al*. Mixed reality with HoloLens: Where virtual reality meets augmented reality in the operating room. Plast Reconstr Surg 2017;140:1066-70.
11. St-Louis E, Miao J, Emil S, Baird R, Bettolli M, Montpetit K, *et al*. Vacuum bell treatment of pectus excavatum: An early North American experience. J Pediatr Surg 2019;54:194-9.
12. Deng X, Huang P, Luo J, Wang J, Yi L, Yang G, *et al*. A novel three-dimensional printed vacuum bell for pectus excavatum treatment: A preliminary study. J Cardiothorac Surg 2020;15:240.
13. Fibla JJ, Molins L. Minimally invasive treatment of pectus excavatum. Minerva Chir 2016;71:38-45.
14. Zou J, Luo C, Liu Z, Cheng C. Cardiac arrest without physical cardiac injury during Nuss repair of pectus excavatum. J Cardiothorac Surg 2017;12:61.
15. Mao YZ, Tang S, Li S. Comparison of the Nuss versus Ravitch procedure for pectus excavatum repair: An updated meta-analysis. J Pediatr Surg 2017;52:1545-52.
16. Kuyama H, Uemura S, Yoshida A. Recurrence of pectus excavatum in long-term follow-up after the Nuss procedure in young children based on the radiographic Haller index. J Pediatr Surg 2020;55:2699-702.
17. Fortmann C, Petersen C. Surgery for deformities of the thoracic wall: No more than strengthening the patient's self-esteem? Eur J Pediatr Surg 2018;28:355-60.
18. Park HJ, Kim JJ, Park JK, Moon SW. Effects of Nuss procedure on thoracic scoliosis in patients with pectus excavatum. J Thorac Dis 2017;9:3810-6.
19. Velazco CS, Arsanjani R, Jaroszewski DE. Nuss procedure in the adult population for correction of pectus excavatum. Semin Pediatr Surg 2018;27:161-9.
20. Gonzalez-Rivas D. Uniportal thoracoscopic surgery: From medical thoracoscopy to non-intubated uniportal video-assisted major pulmonary resections. Ann Cardiothorac Surg 2016;5:85-91.
21. Cafarotti S, Memoli E, Patella M, Rugel G, Minerva EM, Mendoza CM, *et al*. Uniportal VATS for pectus excavatum: The Southern Switzerland experience. Eur Rev Med Pharmacol Sci 2020;24:9008-11.
22. Ben XS, Deng C, Tian D, Tang JM, Xie L, Ye X, *et al*. Multiple-bar Nuss operation: An individualized treatment scheme for patients with significantly asymmetric pectus excavatum. J Thorac Dis 2020;12:949-55.
23. Wang L, Guo T, Zhang H, Yang S, Liang J, Guo Y, *et al*. Three-dimensional printing flexible models: A novel technique for Nuss procedure planning of pectus excavatum repair. Ann Transl Med 2020;8:110.
24. Lin KH, Huang YJ, Hsu HH, Lee SC, Huang HK, Chen YY, *et al*. The role of three-dimensional printing in the nuss procedure: Three-dimensional printed model-assisted nuss procedure. Ann Thorac Surg 2018;105:413-7.
25. Fang C, An J, Bruno A, Cai X, Fan J, Fujimoto J, *et al*. Consensus recommendations of three-dimensional visualization for diagnosis and management of liver diseases. Hepatol Int 2020;14:437-53.
26. Zhang X, Jiang T, Chen D, Wang Q, Zhang LW. Three-dimensional liver models: State of the art and their application for hepatotoxicity evaluation. Crit Rev Toxicol 2020;50:279-309.
27. Bercik MJ, Kruse K 2nd, Yalizis M, Gauci MO, Chaoui J, Walch G. A modification to the Walch classification of the glenoid in primary glenohumeral osteoarthritis using three-dimensional imaging. J Shoulder Elbow Surg 2016;25:1601-6.
28. Choy WJ, Parr WC, Phan K, Walsh WR, Mobbs RJ. 3-dimensional printing for anterior cervical surgery: A review. J Spine Surg 2018;4:757-69.
29. Parr WC, Burnard JL, Wilson PJ, Mobbs RJ. 3D printed anatomical (bio) models in spine surgery: Clinical benefits and value to health care providers. J Spine Surg 2019;5:549-60.