The Role of Three-Dimensional Printing in the Nuss Procedure: Three-Dimensional Printed Model-Assisted Nuss Procedure

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Background. **The Nuss procedure is a minimally invasive surgery for pectus excavatum. Success of the Nuss procedure is dependent on a previously bent pectus bar that is shaped to the desired curvature of the chest wall. Traditionally, the size and curvature of the metallic pectus bar are determined by trial and error. Herein, we introduce a novel design method for the metallic pectus bar to optimize the bar curvature and outcome after the Nuss procedure.**

Methods. **From August 2016 through March 2017, 10 consecutive patients with pectus excavatum underwent the three-dimensional (3D) printed model–assisted Nuss procedure. The computed tomography images were used to generate a 3D thorax model of pectus excavatum. The 3D models of personalized pectus bar curvature were completed by computer-aided design. Herein, we report the demographic data, treatment outcomes, and radiographic findings.**

Results. **All patients with pectus excavatum received one pectus bar insertion. The mean age was 19.80 ± 4.73 years (range, 12 to 26). The mean preoperative Haller index was 3.48 ± 0.35 (range, 3.06 to 3.95). We advantageously utilized preoperative planning; the mean interval change of the Haller index was 20.71% ± 4.63%. With the benefit of 3D printed model simulation, the surgical duration was 59.8 ± 23.2 minutes (range, 32 to 107). No patient had adverse events after operation.**

Conclusions. **Our initial results revealed that the 3D printed model–assisted Nuss procedure reduces the surgical duration and facilitates an optimal morphological outcome.**

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Pectus excavatum (PE) is a congenital anomaly of the chest wall that is characterized by a posterior depression of the sternum and adjacent costal cartilages. The Nuss procedure, first reported in 1998 by Nuss and associates [1], is the placement of a pectus bar to elevate the sternum anteriorly. Although the Nuss procedure has become the standard of surgical intervention for PE [2], the size and curvature of the pectus bar is determined by trial and error by repeated insertion and flipping of the pectus bar [3–5]. The key steps of this procedure require an experienced surgeon to bend the pectus bar during the operation and select the correct intercostal space for insertion of the bent pectus bar. When the chest wall deformity is more severe, it is more difficult for the surgeon to satisfactorily perform these procedures, which are bothersome and potentially hazardous [4]. Thoracic three-dimensional (3D) printed models can assess anatomic structures and be used for advanced preoperative planning [6]. We used new 3D printing technology to attempt to bend the pectus bar to match the chest wall contours and prevent flipping after placement. Utilizing this model, we designed a personalized 3D printed model of the pectus bar, predicted the morphologic outcomes, reduced the pectus bar design time on the table, and potentially reduced the surgical duration of the procedure. Herein, we report our results from the 3D printed model–assisted Nuss (3DPMAN) procedure that was performed in 10 PE patients. The initial results of this novel 3DPMAN procedure show that it is feasible, easy, convenient and satisfactory.

Patients and Methods

This study was a prospective study that collected 3D printing medical applications, including a 3DPMAN database, from a 1,700-bed tertiary medical center. The study was reviewed and approved by the Tri-Service General Hospital Research Ethics Committee (approval number 1-105-05-100).

Study Design and Patients

We began performing the Nuss procedure for the treatment of PE in 2005. In August 2016, we began the 3DPMAN procedure program to treat PE using 3D

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printing technology to simulate the surgical intervention and guide pectus bar design. The patients selected for a 3DPMAN procedure met the following criteria: (1) progression of the deformity; (2) exercise intolerance; (3) progressive chest pain or dyspnea; (4) cardiopulmonary deficits; (5) Haller index (HI) greater than 3.25 (ratio of the transverse thoracic dimension to the sternovertebral at the most depressed point, as detected on computed tomography [CT] of the chest); (6) cardiac compression; and (7) psychosocial effects [7]. The patients who had previously undergone the Nuss procedure with more than pectus bar placement were excluded.

In all, 10 consecutive patients received 3DPMAN and were included in this prospective study. There were 9 boys and 1 girl with a mean age of 19.8 years (range, 12 to 26). The mean HI based on CT scans was 3.48 ± 0.35 (range, 3.06 to 3.95; Table 1). The parents' consent for the operation was obtained after they had been informed of the surgical indications, complications, possible outcomes, and limitations of the Nuss procedure. Patient characteristics, surgical duration, postoperative hospital stay, efficiency of operation, and postoperative complications were recorded (Table 1).

On a chest radiograph, the sternovertebral point was identified as the most posterior projection of the sternum from a lateral view. The transverse diameter was measured on the posterior-anterior view at the same vertebral level as the sternovertebral measurement made from the lateral view. These radiologic measurements for chest radiograph and CT were independently detected and calculated by a radiologist (H.-H. H) and a thoracic surgeon (Y.-J. H.). The HI was calculated using preoperative CT and postoperative chest radiograph values. The HI interval change was defined as the preoperative HI (measured by preoperative CT) minus the postoperative HI (measured by postoperative chest radiograph). The HI improvement percentage was defined as the interval change of HI divided by the preoperative HI (measured by preoperative CT).

Surgical Procedure

The surgical 3DPMAN procedure is summarized in Figures 1 and 2. The 3DPMAN technique with modifications was attempted in all patients. A modified Nuss repair was performed as described previously [7]. Briefly, bilateral vertical skin incisions approximately 1.5 cm to 2.5 cm were made near the middle axillary line. A thoracoscope was used to inspect the thoracic cavity for mediastinal structures and to monitor insertion of the introducer, which was inserted into the right thoracic cavity behind the sternum and anterior to the pericardium. As the substernal tunnel was created, a 28F chest tube was fixed on the introducer and retracted. A Lorenz pectus bar (Lorenz Surgical, Jacksonville, FL) previously bent identically to the 3D printed model was connected to the chest tube and slid across the anterior mediastinum. After the pectus bar was flipped and fixed in the correct position, the pectus bar was attached to the ribs with a 1.0-mm stainless steel wire or suture to prevent pectus bar rotation. Two Jackson-Pratt drainage tubes were inserted bilaterally into the pleural cavities. Patient-controlled epidural analgesia was used to treat postoperative pain for 2 or 3 days. All patients received postoperative posterior-anterior and lateral chest radiograph as a radiologic follow-up at 1, 3, 6, and 12 months. The postoperative HI measurement was determined at the 1-month follow-up to evaluate the results of the Nuss repair.

Table 1. Patient Demographics and Baseline Characteristics

Variables	Values
Age, years	19.80 ± 4.73
Male	9 (90)
Height, cm	169.00 ± 11.16
Weight, kg	54.32 ± 12.50
Body mass index, kg/m^2	18.71 ± 2.58
Preoperative maximal transverse diameter, cm	25.48 ± 3.08
Preoperative narrowest AP length of chest, cm	7.22 ± 1.09
Preoperative Haller index	3.48 ± 0.35
Number of pectus bars	1

Values are mean ± SD or n (%).

AP = anteroposterior.

Three-Dimensional Printing Technique

A spiral CT of the chest was performed from the upper edge of the first thoracic rib to the lower edge of the 12th rib. Computed tomography images (Fig 1A) were saved in Digital Imaging and Communications in Medicine (DICOM) format with a slice thickness of 1 mm. The CT images were loaded into the 3D reconstruction software OsiriX (Pixmeo, Geneva, Switzerland) [8] to generate a 3D thorax PE model, including the spine, sternum, clavicle, ribs, and costal cartilages. The soft tissue region that was not of interest was deleted. The images were exported as stereolithography (STL) files for Meshmixer, a 3D mashups and remixes software package (Autodesk, San Rafael, CA). The original chest contour was adjusted with anterior movement of the sternum by 2.22 ± 1.05 cm, as described in our previous report for preventing undercorrection or overcorrection (Fig 1B) [9]. The prediction of the postoperative chest contour model and design of the personalized pectus bar for prebending were completed with computer-aided design (Fig 1C). The 3D model of the pectus bar was saved as an STL to print with a regular desktop 3D printer (UP BOX+) using polylactic acid (0.2 mm layer thickness). These 3D models of the pectus bars were then sterilized for clinical simulation (Fig 2).

Data Collection and Analyses

The main outcomes were recorded. The primary outcomes were the interval change of HI, surgical duration, number of pectus bars, adverse events, duration of chest drainage, and duration of postoperative hospital stay. The secondary outcomes were complications occurring after 30 days; 1, 3, 6, and 12 months of follow-up data; delayed complications; 3D model printing time; and 3D printing model postprocessing time. The demographic