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ORIGINAL ARTICLE

Increase in intrathoracic volume in pectus excavatum patients after the Nuss procedure

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Abstract In this study, we present finite element analysis models to calculate the increase in intrathoracic volume of pectus excavatum patients after the Nuss procedure. One virtue of our approach is that the measurement of the intrathoracic volume has no time difference and is not affected by postoperative pain, which cannot be achieved with a 2-year difference between pre- and postoperative pulmonary function testing or any other clinical method. The calculations show that the intrathoracic volume of pectus excavatum patients increased by approximately 2.72–8.88% after the Nuss procedure. The increment curve was patient-dependent, although the increment behavior was similar among the six patients examined. The curve of the increase became flat when the elevating force exceeded 80 N or the displacement of the lower sternal end exceeded 2.6 cm in half of our cases.

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1 Introduction

Pectus excavatum (PE) is a common chest wall malformation [4]. The cause of this defect is thought to be the excessive growth of the costal cartilage, resulting in the formation of a concave anterior chest wall [5]. In 1998, Nuss introduced a minimally invasive technique for repairing pectus excavatum [12]. In this procedure, the depression of the sternum is corrected by inserting a metal Nuss bar without removing the costal cartilage. The Nuss procedure may increase the intrathoracic volume of the PE patient's deformed chest wall, thereby improving the patient's pulmonary function. In this study, we present an intrathoracic volume measurement method, employing finite element analysis (FEA) models.

In our previous research [2], we created several finite element models to investigate the biomechanical changes in PE patients after the Nuss procedure. It provides a convenient way to calculate the stress and strain induced in the chest wall by the Nuss procedure, and the deformation of the chest wall is obtained simultaneously. Here, we applied this finite element model and the factors that may influence the increase in intrathoracic volume to measure the intrathoracic volume change in PE patients after the Nuss procedure. One virtue of our approach is that the measurements of the preoperative and postoperative intrathoracic volumes lack any time difference between the pulmonary function testing and are not affected by postoperative pain, which cannot be achieved with any current clinical method.

2 Methods

2.1 Finite element models

In this study, six symmetric-type PE patients were chosen for analysis, to eliminate factors related to an asymmetric configuration of the chest wall. As shown in Table 1, the median age of the subjects was 6.6 years (range, 5–8) and the median Haller's chest wall compression index [7] was 4.5 (range, 3.6–5.3). The second patient was female, and the others were males. All six patients underwent preoperative computed tomography (CT), which was performed with a 16-slice scanner (Siemens SOMATOM Sensation 16) using a previously described protocol [1]. Anterio-posterior and lateral chest X-rays were taken immediately after the operation. The upward displacement was calculated between the preoperative CT and postoperative chest lateral view, to avoid any effect of the time difference between the measurements. There may be a minimal difference between the measurement of the CT and chest X-ray film, but this is acceptable [11].

This study was approved by the Ethics Committee of our hospital on 4 April 2006 (Internal Review Board 94-934B). Informed consent was obtained from the guardians of all the subjects.

Finite element models were created based on individual preoperative CT data and analyzed with the ANSYS FEA software. The six FEA models, which included the ribs, costal cartilage, and sternum, were created using Amira software (Visage Imaging, Inc., San Diego, CA). Geometric models were reconstructed from preoperative CT slices, and the FEA models were generated by meshing the geometric models with tetrahedral elements. The material properties of bone and cartilage were based on the work of Yang and Wang [15]. An elastic modulus of 11.5×10^9 Pa (11.5 GPa) was chosen for the ribs and sternum, and a value of 12.25×10^6 Pa (12.25 MPa) was assumed for the pectus costal cartilage, which is about half the value for normal cartilage, as suggested by Feng et al. [3]. Each FEA model consisted of about 320,000 tetrahedral elements. As the material properties of muscle and skin are much less than those of the ribs, sternum, and costal cartilage, we omitted these components from our biomechanical models [1]. Moreover, based on clinical observations, the shape of the vertebral column did not appear to be remodeled in any of the six patients after the Nuss procedure. Thus, the displacement of the joints between the rib and spine was assumed to be steady.

In the Nuss procedure, the concave side of the Nuss bar is placed under the sternum, and the bar is then turned around forcibly to raise the depressed sternum. After the depressed sternum is raised completely, several reacting forces are generated in the chest wall. The Nuss bar provides an elevating force to raise the depressed sternum. To preserve the equilibrium of the Nuss bar, two supporting forces were generated simultaneously at the exits of the intercostal muscle, and these forces, called the rib support forces, were passed to the ribs above and below the exits. The actual upward displacement of the lowest point of the sternum was calculated from the difference between the preoperative CT and postoperative chest X-ray films. The FEA models simulated the same elevation distance to calculate the deformation of the chest wall of PE patients after the Nuss procedure.

2.2 Intrathoracic volume measurement

After the reconstruction of the FEA models, the chest wall deformation after surgery consisted of only the ribs, sternum, and costal cartilage. The intrathoracic volume cannot be measured directly from these models. To overcome this, we developed an intersection method to compute the intrathoracic volume by inserting a set of cutting planes into the FEA model, similar to the axial plane of a CT scan. These planes are parallel and equidistant (about 2.6 mm) along the longitudinal axis of the model, from the apex of the lung to the dome of the diaphragm, containing most of the volume of the lungs. The intersecting points of a cutting

Table 1 Demographic and biomechanical data

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Sex/age	M/8	F/7	M/7	M/6	M/5	M/13
Pectus index	5.3	4.7	5.2	3.7	3.6	4.7
Elevation of the end of the sternum (cm)	4.47	3.40	3.90	3.54	3.75	4.10
Simulation results						
Simulated displacement of the end of the sternum (cm)	4.49	3.43	3.90	3.55	3.79	4.11
Loading force at the end of the sternum (N)	140	120	190	80	70	128
Increase in the intrathoracic volume (cm^3)	89.98	54.63	29.76	54.24	107.04	171.51
Increase in the intrathoracic volume (%)	6.09	5.05	2.72	4.43	8.88	7.64

M male, *F* female, *N* Newtons

plane were calculated and depicted in a picture with 512 × 512 pixels (Fig. 1). These data were imported into Amira, and the relative segment of the contour of the thoracic cavity was manually labeled on each picture, relying on our professional experience. Figure 2 shows the relative contour segments of the thoracic cavity for the preoperative and postoperative FEA models.

After the contour of the thoracic cavity was labeled on each imported picture, these segments were assembled into a 3D model in Amira. Then, the thoracic volume was calculated with the closed surface of the thoracic cavity model. Finally, the volume difference between the two models was calculated. The calculated volume difference is an estimate of the final total difference in the intrathoracic volume.

3 Results

The biomechanical data used for the six FEA models are summarized in Table 1. The intrathoracic volumes of these postoperative PE patients increased by 2.72–8.88%. Figure 3 plots the intrathoracic volume increment against the elevating force and the displacement of the end of the sternum. Three patients' curves became level when the elevating force or the displacement of the lower sternum exceeded a certain value: patient #3 at 80 N and 3.0 cm, patient #4 at 50 N and 2.8 cm, and patient #2 at 100 N and 3.2 cm. The increment curve was patient-dependent, although the behavior was similar in all six patients.

4 Discussion

Pulmonary function testing is helpful in defining the degree of functional impairment in patients during the course and treatment of pectus excavatum. The measurement of respiratory function in infants and young children can be difficult, not least because of the lack of cooperation [8]. Many studies have attempted to determine an improvement in pulmonary function after thoracoplasty [9, 10, 13]; however, the results of all of these studies suffer from the time differences between the measurements. It was difficult to assess whether the improvement in pulmonary function was the result of the surgery or was simply due to the growth of the chest. In this study, the intrathoracic volumes of the six PE patients increased by 2.72–8.88%. If we assume that the volumes of the mediastinum and heart do not change, then these increases in intrathoracic volume can be translated into increments of lung volume, providing indirect evidence that the Nuss procedure has a positive effect on pulmonary function.

With modern CT technology and software, we were able to apply a very fine-resolution FEA model to simulate the human chest wall reaction to the force produced in the Nuss procedure. The models were constructed based on the mechanical theory and with an accuracy that could not be dreamed of only a few years ago. Although each model is of a simplified human chest wall, the models still provide some mechanical data that cannot be obtained from controlled clinical studies. The validity of our model can be verified from previous studies, in which the forces needed to elevate the sternum end during thoracoplasty were measured. Fonkalsrud and Reemtsen reported that the children with PE who are younger than 11 years required a force of about 15.3 lbs (68.058 N) to raise the sternum to the desired position [6]. Weber et al. found that for males aged 5–17 years, the force required to correct PE was 181 ± 48.3 N [14]. The forces calculated in our simulations are similar to the forces reported in these previous studies. The similarity between the postoperative

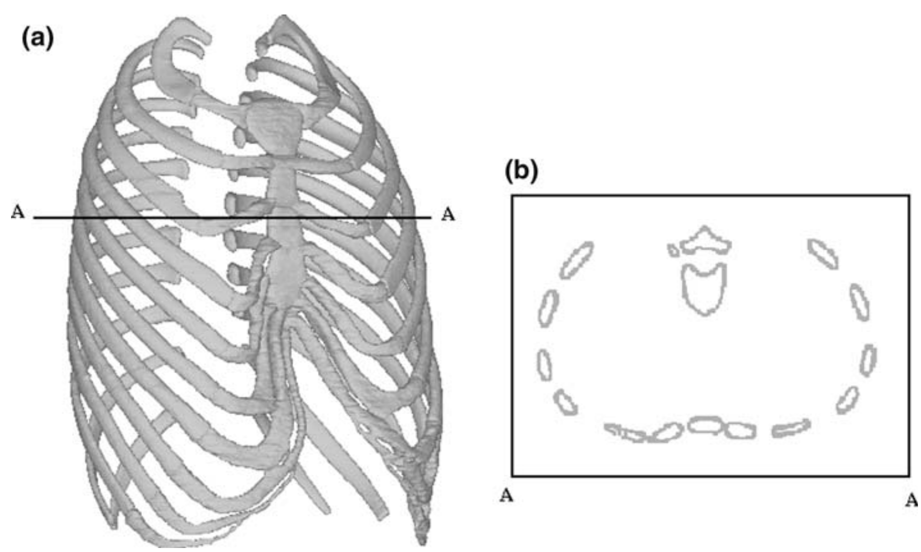

Fig. 1 **a** Finite element pectus excavatum model with (**b**) cutting plane along A–A

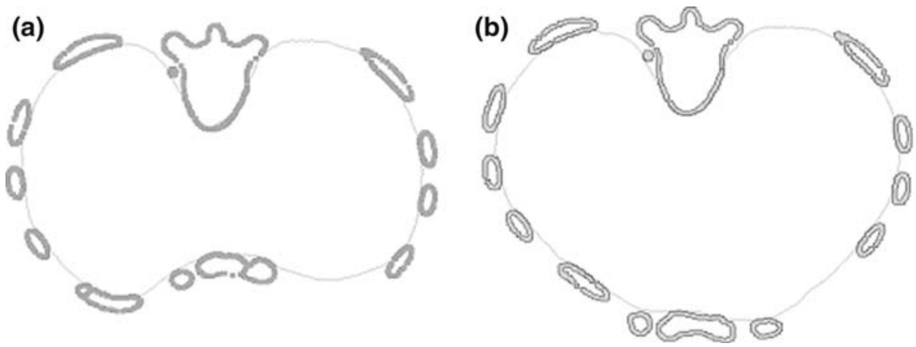

Fig. 2 Intersection points between the plane and the preoperative and postoperative finite element models. **a** Preoperative cross section. **b** Postoperative cross section

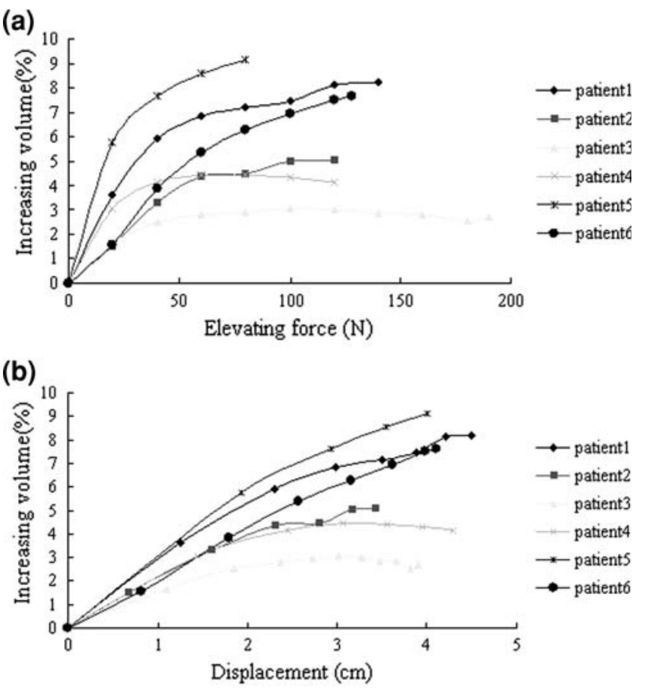

Fig. 3 Intrathoracic volume plotted against the increase in the **a** elevating force and **b** elevation of the end of the sternum

appearance of the chest wall and our simulation also supports the validity of our model.

However, the intrathoracic volume measurements calculated from our models may have limitations, because of the simplifying assumptions used. A more complex model that incorporates the intercostal muscles and joints should be developed, to improve the accuracy and usefulness of FEA in the Nuss procedure.

5 Conclusions

In this study, we applied a rib cage FEA model to measure intrathoracic volume changes. The calculated results show that there is a definite but minimal increase of intrathoracic volumes which might be beneficial to patients' pulmonary function.

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