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Research Article

Cardiopulmonary Impact after Minimally Invasive Repair of Pectus Excavatum

Duk Hwan Moon[1], Chul Hwan Park[2], Wongi Woo[1], Seung Hwan Song[3], Tae Hoon Kim[2], Sungsoo Lee[1*]

[1]Department of Thoracic and Cardiovascular Surgery, Gangnam Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea

[2]Department of Radiology and Research Institute of Radiological Science, Gangnam Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea

[3]Department of Thoracic and Cardiovascular Surgery, Sanggye Paik Hospital, Inje University College of Medicine, Seoul, Republic of Korea

[*]**Corresponding author:** Sungsoo Lee, Department of Thoracic and Cardiovascular Surgery, Gangnam Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea

Abstract

Background: Surgical correction of Pectus Excavatum (PE) has been primarily focused on cosmetic benefit and psychological improvement. However, this study focuses on cardiopulmonary function; cardiac indices, as well as lung volume and pulmonary vascular distribution, are compared before and after surgery.

Methods: This prospective observational study included patients who have received Nuss operation for PE in a single institution between May 2018 and July 2019. The pre and 3-month postoperative cardiac indices [End-Diastolic Volume (EDV), End-Systolic Volume (ESV), Stroke Volume (SV), Ejection Fraction (EF)] were measured using cardiac magnetic resonance image (MRI). Additionally, lung volume and pulmonary vascular perfusion on each lobe were evaluated using Dual Enhancement Computed Tomography (DECT).

Results: This study included 12 patients; the average age was 16.9±4.4 years, and nine (75%) were male. The median ESV and EF values for the right ventricle showed a significant difference between the pre and post-operative measurements (74.9 mL vs 51.2 mL, p=0.008; 50.7 % vs 57.7 %, p = 0.006, respectively). The relative volume of the Right Upper Lobe (RUL) was increased postoperatively (16.1 ± 2.1% vs 17.2 ± 2.9, p=0.028), albeit without significant absolute change in the total lung volume. Similarly, there was no significant difference between the pre and post-operative pulmonary vascular perfusion on each lobe.

Conclusion: The findings of this study suggest that corrective surgery may improve the right ventricular function in PE patients. However, its impacts on lung volume and pulmonary vascular perfusion were inconclusive.

Introduction

Pectus Excavatum (PE) is one of the most common chest wall deformities. It is usually diagnosed in childhood, and the incidence is one in 400. It is known to be about four times more common in males. PE patients generally suffer from psychological stress that arises from having low self-esteem and confidence related to chest shape, impacting daily life [1-3]. Aside from these psychological issues, however, it is known that some PE patients also experience respiratory symptoms (dyspnea on exertion, non-specific chest pain, wheezing) and cardiovascular discomfort (palpitation, fatigue, dyspnea) [4]. Nuss operation via the bar insertion technique is the standard, less-invasive surgical treatment for repairing PE. Previous studies regarding Nuss operation have focused much on the cosmetic outcome of the chest wall, comparing the pre and post-operative shape of the chest wall. However, there has not

been much attention on its cardiopulmonary benefit. In PE, chest wall restriction and decreased thoracic cavity volume may cause a decrease in the filling of the ventricles. Several studies reported that the compression in cardiac chambers causes a decrease in the left ventricular ejection fraction, suggesting that a correction of PE would improve cardiac function. However, evidence for this is not sufficient because echocardiography [5,6] or treadmill test [7] has been the only assessment used to evaluate cardiac function.

In addition, many studies evaluated the postoperative respiratory improvement in PE patients, using the pulmonary function test and exercise treadmill test as primary assessment tools [1,2,8]. To the best of our knowledge, postoperative structural change and its impacts on lung volume and pulmonary vascular supply have not been fully elucidated in the literature. Hence, the present study attempts to fill this gap, evaluating the impacts of Nuss operation on cardiopulmonary function by measuring cardiac function, pulmonary vascular supply, and lung volume. Cardiac Magnetic Resonance Imaging (MRI) and Dual-Enhancement Computed Tomography (DECT) were used to evaluate the change in lung volume and pulmonary vascular distribution.

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Study Design

This prospective observational study was approved by the Institutional Review Board of Gangnam Severance Hospital (No.3-201-0392). Patients who visited the outpatient clinic for PE and consented to surgical treatment were included in this study. Patients had surgery for cosmetic concerns and there was none who had significant functional impairments in cardiopulmonary function. The consent was informed to all patients including their parents and written consents were obtained from patients or parents. We ensured all participant that their data would be fully anonymized before we assess them. Cardiac MRI was performed one day before surgery and three months after surgery at the outpatient clinic. In addition, DECT was performed before the operation and three months after the surgery. A skilled radiologist reviewed the cardiac MRI and DECT images.

Surgery

A single surgeon performed all surgical procedures. Patients were in supine position, with both arms hanging freely on the overhead crossbar on the operating table. The entire anterior chest and both groins were prepared and draped. After draping the thorax, the crane elevator was set up, and wire sutures were then passed through the anterior area of the sternum and lifted by the crane elevator. Skin incisions - 1cm in length - were made on both lateral chests. The bars were configured based on the characteristics of the patient's chest wall. After a single-bar

insertion, the decision to add an additional bar was made based on the degree of correction of the depressed chest wall after rotation and whether the correction was complete or not, or whether the overall outcome was aesthetically pleasing. If it was determined that an additional bar was necessary, either a crossbar insertion technique or parallel bar insertion technique, as appropriate, was used for two-bar insertion. In the case of cross bar insertion, the first bar penetrated diagonally through the target right lower toward the left upper intercostal spaces. Using a pectus bar rotator, the bar was turned over, and the second bar penetrated diagonally through the target right upper toward the left lower intercostal spaces. The point where the bars crossed lifted not only the most depressed area, but also the overall chest wall of the patient. In the case of parallel bar insertion, the first bar was inserted transversely at the deepest point of the chest, followed by a transverse insertion of the second bar at one or two intercostal levels above the first. In both methods, the bars were fixed by bridge plates (primemed, Seoul, Korea). We placed two small caliber hemovac drainages in the pleural spaces through the wounds. Intravenous pain control administration system was routinely initiated after the operation.

Cardiac MRI: Imaging protocol and analysis methods

Cardiac MR imaging was done using a 1.5-T MR scanner (Magnetom Avanto; Siemens Medical Solutions, Erlangen, Germany) with a 12-element phased-array coil, maximum gradient strength of 45 mT/m, and maximum slew rate of 200 mT/m/s. After localization of the heart, Cine-MR imaging with horizontal long-axis, vertical long-axis and contiguous short-axis planes was obtained with a balanced steady-state free precession (b-SSFP) sequence or spoiled gradient echo. Imaging parameters were retrospective ECG gating, 25 frames/R-R interval, 8mm of slice thickness, and 10mm of slice spacing. All MR images were transferred to a picture archiving and communication system (PACS) (Centricity 4.0; GE Medical Systems,Mt Prospect, IL, USA), as well as to a commercially available cardiac dedicated software (cvi42, Circle Cardiovascular Imaging Inc., Calgary, AB, Canada) for functional analysis. On the short-axis cine-MR images, the end-diastolic and end-systolic images were selected for the left ventricle and right ventricle, separately. The endocardial borders of the left ventricle (LV) and right ventricle (RV) were carefully delineated semi-automatically on the end-diastolic and end-systolic images. End-systolic volume (ESV, mL) and end-diastolic volume (EDV, mL) of LV and RV were automatically calculated. Then, the stroke volume (SV, mL) and ejection fraction (EF, %) of LV and RV were calculated as follows: $SV = EDV - ESV$, $EF = (SV / EDV) \times 100$. The papillary muscles and trabeculations were considered to be a part of the myocardium and were excluded from the cavity (Figure 1).
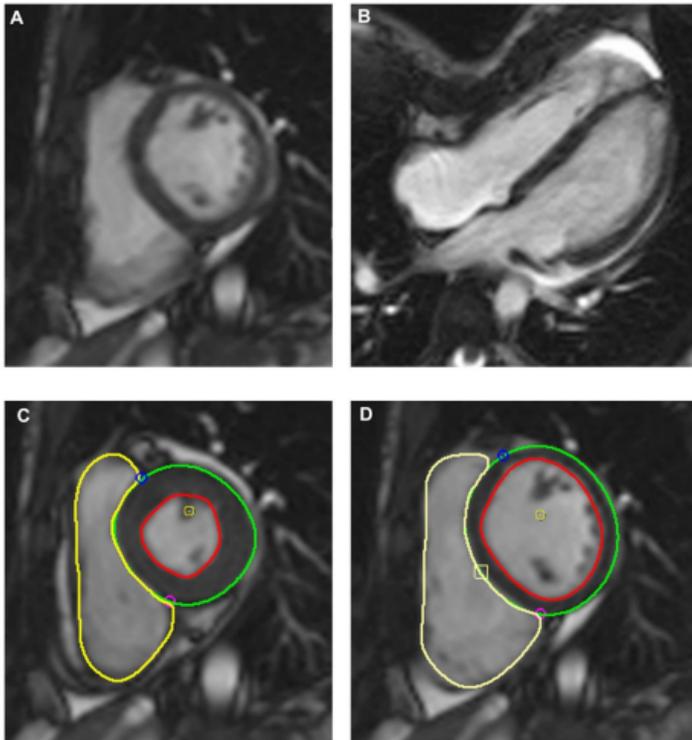
Figure 1: Cardiac MR analysis for ventricular functional evaluation. Cine-MR images were obtained from patients with pectus excavatum with contiguous short-axis planes (A) and long-axis planes (B). On the end-diastolic (C) and end-systolic images (D), endocardial borders were carefully delineated semi-automatically. Then the end-systolic volume, end-diastolic volume, and ejection fraction were obtained from left ventricle and right ventricle.

DECT: Imaging protocol and analysis methods

All chest DECT scans were performed using a 256-detector row CT scanner (Revolution CT, GE Healthcare, Milwaukee, WI, USA) in supine position. CT scanning was performed during a single breath-hold at the end-inspiratory pause. After scout image acquisition, the contrast-enhanced chest CT scans were done using the dual-energy spectral CT scanning mode with scan parameters as follows: helical scan with 80mm detector width, fast kVp switch technique between tube voltages of 80 and 140 kVp; Noise index = 28; helical pitch, 0.992:1. For contrast-enhancement, 1.2 ml/kg of non-ionic iodine contrast media ioversol (Optiray 350, Tyco Healthcare, Kantata, Canada)) was administrated for 1 minute via an antecubital vein, followed by 20ml saline flush with 2ml/sec flow rate. CT scans covered from the thyroid gland to the adrenal glands with craniocaudal direction. After CT scans, axial CT images were reconstructed as a slice thickness of 0.625 mm with 0.625mm increment using the Gemstone Spectral Imaging (GSI) software on an advanced workstation 4.6 (AW 4.6; GE Healthcare).

By using axial CT images, the three-dimensional lung volume was measured using a commercially available reconstruction program with a default range from -200 to -1024 HU. Then each lobe was segmented semi-automatically by delineating a few lines along the major fissure or minor fissure manually. After semi-automatic lobe segmentation, each lobe was carefully corrected manually by an experienced radiologist. Then each lobe volume was automatically measured. After lobe volume calculation, iodine maps were automatically generated form a combination of the 140-kV and 80-kV data using dedicated post-processing software (AW 4.6; GE Healthcare). Then lobe segmentation data was merged with iodine maps and mean iodine concentration was calculated from each lobe. Total amount of iodine in each lobe was calculated by multiplying the mean iodine concentration and the volume of each lobe. The total amount of iodine in each lobe was used as a representative marker of perfusion (Figure 2).
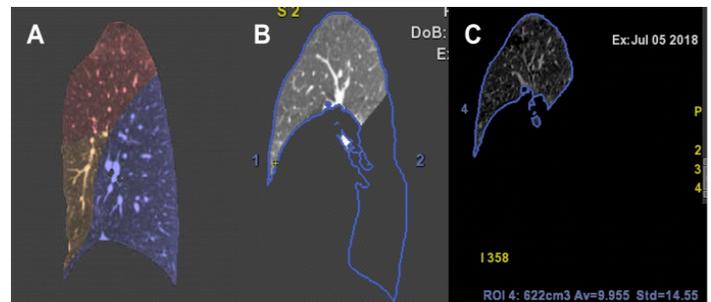

Figure 2: DECT analysis for lobe specific perfusion evaluation. By using axial CT images, each lobe was segmented semi-automatically **(A and B).** After iodine maps was generated form a combination of the 140-kV and 80-kV data using dedicated post-processing software, lobe-specific iodine amount was calculated by merging lobe segmentation data and iodine maps **(C).**

Statistical Analysis

All measured data, which were expressed as mean and standard deviation, were analyzed by using SAS version 9.4 (SAS Institute, Cary, NC, USA), R package version 3.6.0. Relative pulmonary lobar volume and perfusion distribution were presented as a percentage of total lung size. MRI and DECT results - before and after Nuss procedure - were assessed using paired t-test. $P < 0.05$ was considered statistically significant.

Results

Baseline Characteristics and Operative Results

This study included 12 patients; the average age was 16.9 ± 4.4 years, and nine patients (75%) were males. The median hospital days was 5 days, with a range from 3 to 7 days. All patients, except

one, used two bars. Of these 11 patients, six patients received the cross-bar technique, whereas five patients received the parallel bar insertion technique. One patient among those who received the cross-bar technique, received an additional, third bar. There was a significant decrease in the Haller index, from 5.53 ± 4.33 before surgery to 2.79 ± 0.51 after surgery (p = 0.03). There was no reported complication or death related to surgery (Table 1).

		Total (N=12)
Age, mean ± SD, years		16.9 ± 4.4
Male : Female		9 : 3
Two bars insertion technique	Cross bar	7
	Parallel bar	5
Haller index (p=0.03*)	Preoperative	5.53 ±4.33
	Postoperative	2.70 ± 0.51
Hospital stay (days)		5 [3 - 7]
*. No operative mortality and morbidity occurred		

Table 1: Demographic and operative data of patients.

Change in cardiac hemodynamic indices of the right and left ventricles after surgery

The preoperative median values for EDV, ESV, SV, and EF of Left Ventricle (LV) were 115.4 mL, 39.1 mL, 74.0 mL, and 65.4 %, respectively. The postoperative median values for these were 111.5 mL, 41.7 mL, 71.1 mL, and 63.4 %, respectively. None of these showed a statistically significant difference between the pre- and postoperative values (Table 2, Figure 3). The preoperative median values for EDV, ESV, SV, and EF of Right Ventricle (RV) were 152.8 mL, 74.9 mL, 73.6 mL, and 50.7 %, respectively. The postoperative median values for these were 126.2 mL, 51.2 mL, 69.2 mL, and 57.7 %, respectively. Among these cardiac indices for RV, ESV and EF showed a significant difference between the preoperative and postoperative median values (74.9 mL vs 51.2 mL, p = 0.008; 50.7 % vs 57.7 %, p = 0.006, respectively) (Table 2, Figure 4).

Left Ventricle			
Parameters	Preoperative	Postoperative	p-value
EDV (mL)	113.2 ± 22.5	114.9 ± 22.3	0.785
ESV (mL)	40.2 ± 9.2	42.7 ± 9.5	0.363
SV (mL)	73.3 ± 14.1	72.3 ± 13.8	0.741
EF (%)	64.7 ± 3.1	63.0 ± 2.7	0.130
Right Ventricle			
Parameters	Preoperative	Postoperative	p-value
EDV (mL)	142.3 ± 28.7	126.9 ± 16.2	0.031*
ESV (mL)	70.5 ± 17.8	55.3 ± 10.6	0.002*
SV (mL)	71.8 ± 13.0	71.7 ± 13.5	0.976
EF (%)	50.8 ± 4.3	56.3 ± 6.4	<0.001*

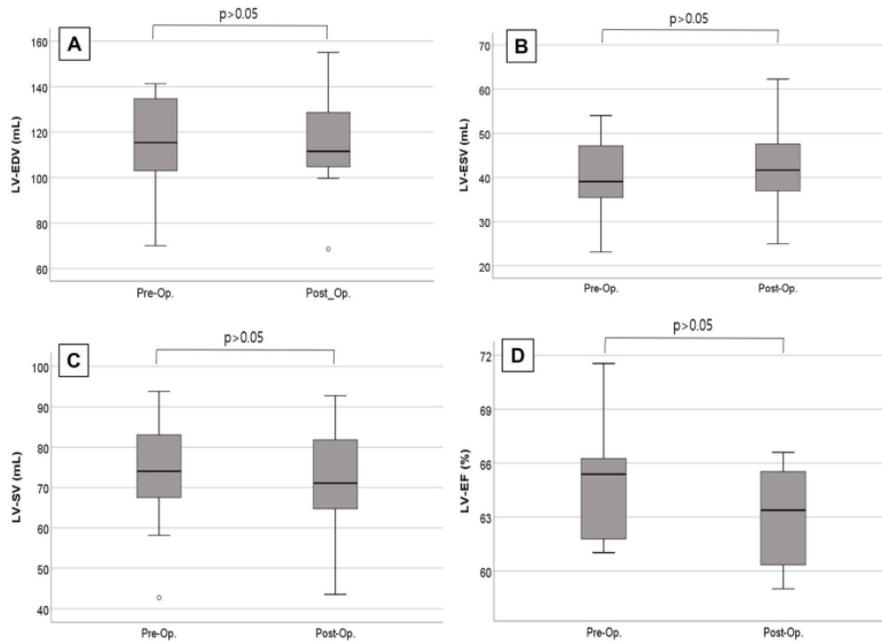**Table 2:** Cardiac MRI parameters for both ventricles.

Figure 3: Left ventricular functional change after Nuss operation in patients with pectus excavatum. End diastolic volume **(A),** end systolic volume **(B),** stroke volume **(C)** and ejection fraction **(D)** of left ventricle were not changed statistically after Nuss operation.
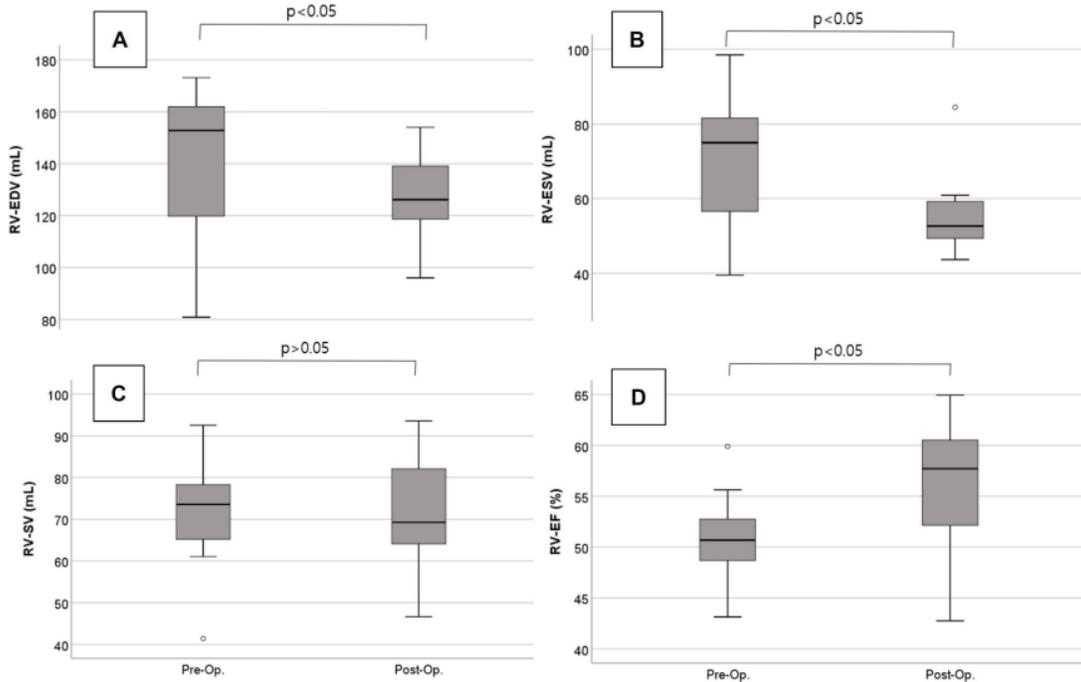

Figure 4: Right ventricular functional change after Nuss operation in patients with pectus excavatum. After Nuss operation , end diastolic volume **(A)** and end systolic volume **(B)** of right ventricle were significantly decreased compared to those of pre-operation. Stroke volume **(C)** was not significantly changed. However, Right ventricular ejection fraction **(D)** was significantly improved after Nuss operation.

Change in lung volume and relative pulmonary vascular distribution

The total lung volume did not show a significant change after the Nuss procedure (Right : 2044 ± 705mL vs 1755 ± 962mL, p=0.133; Left : 1879 ± 606ml vs 1608 ± 663mL, p=0.120). Table 3 shows detailed lung volume and perfusion changes respectively. The preoperative lung volume distribution of RUL, RML, RLL, LUL, and LLL were 16.1 ± 2.1%, 10.4 ± 3.1%, 27.9 ± 3.7%, 23.3 ± 1.6%, and 22.3 ± 2.4%, respectively. The postoperative lung volume distribution of RUL, RML, RLL, LUL, and LLL were 17.2 ± 2.9%, 10.0 ± 2.1%, 27.3 ± 3.1%, 23.9 ± 1.1%, and 21.4 ± 3.9%, respectively. Based on a comparison between pre and postoperative lung volume, there was a significant increase in the relative volume of RUL after the surgery (16.1 ± 2.1% vs 17.2 ± 2.9%, p=0.028).

We compared the relative lung volume and the fraction of perfusion for each lobe. Pre-operatively, there was a significantly higher perfusion in the LLL (Volume: 22.3 ± 2.4% vs Perfusion: 25.1 ± 3.4%, p = 0.005) whereas a significantly lower perfusion in the RML (Volume:10.4 ± 3.1% vs Perfusion: 9.1 ± 2.7%, p=0.002) and LUL (Volume: 23.3 ± 1.6% vs Perfusion 21.4 ± 1.8%, p <0.001). Post-operatively, a similar pattern of perfusion was observed in the LLL, RML, and LUL. However, there was a significant increase in the relative vascular perfusion in the RLL postoperatively (Volume : 27.3 ± 3.1% vs Perfusion : 30.5 ± 5.1%, p =0.010).

Preoperative data				
Lobe	Absolute Volume (mL)	Relative Volume (%)	Relative Perfusion(%)	p-value
RUL	588 ± 165	16.1 ± 2.1	15.8 ± 2.9	0.649
RML	389 ± 168	10.4 ± 3.1	9.1 ± 2.7	0.002*
RLL	1067 ± 423	27.9 ±3.0	28.5 ± 3.6	**0.414**
LUL	876 ± 319	23.9 ± 1.2	21.4 ± 1.8	<0.001*
LLL	878 ± 450	21.4 ± 3.9	25.1 ± 3.4	0.005*
Postoperative data				
RUL	579 ± 161	17.2 ± 2.9	15.5 ± 3.0	0.056
RML	338 ± 115	10.1 ± 2.1	8.9 ± 2.1	0.008*
RLL	961 ± 379	27.4 ± 3.1	30.5 ± 5.1	**0.010***
LUL	827 ± 270	23.3 ± 1.7	21.3 ± 3.9	0.026*
LLL	780 ± 401	22.2 ± 3.5	23.7 ± 4.4	0.001*

Table 3: Lung volume and perfusion measurement data using DECT.

Comment

This study evaluated the impacts of Nuss operation on cardiac function and pulmonary physiology in PE patients. This study found that after the surgery, The Right Ventricle End-Diastolic Volume (RVEDV) and end-systolic volume (RVESV) decreased, while The Right Ventricle Ejection Fraction (RVEF) increased. On the other hand, there was no significant difference in the left ventricle. Also, this research showed a redistribution of pulmonary volume and vascular perfusion after the Nuss procedure. After the operation, the relative size of RUL increased, and the vascular perfusion of RLL also relatively increased. This finding supports that surgical treatment of PE may be beneficial in terms of cardiopulmonary function. Specifically, it provides evidence suggesting that surgical treatment of PE may improve right ventricle function. This study also could initiate further discourse on the change in lung volume and vascular supply after the Nuss operation.

In PE patients, the sternum tends to shift leftward and compresses the heart into the left hemithorax, distorting the shape of the heart and adjacent great vessels. In addition, many studies have tried to measure the change in cardiopulmonary physiology after Nuss operation. Some studies indicated improved cardiopulmonary function after the Nuss operation by performing exercise tolerance tests and pulmonary function test [9-11]. However, such tests are limited in explaining the reasons behind the improvement of it. There are currently several ways to evaluate the postoperative degree of deformity in PE patients. Chest X-rays and CT scans are the mainstay methods. However, due to the risk of radiation exposure that these tests carry, other methods have been developed, including pulmonary function tests [10,12], exercise

tolerance tests [7], arterial blood gas test, and echocardiography [6,13]. Recently, cardiac MR has shown its potential as a reliable, non-invasive diagnostic tool [14]. It is considered influential in assessing thoracic anatomy, cardiac function, pulmonary vascular anatomy and perfusion, and blood flow and circulation [15]. Therefore, the present study used cardiac MR to objectively investigate the difference between pre and post-operative cardiac function in PE patients.

As the heart tries to compensate for this anatomic distortion due to PE, the basal segment of the RV is thought to be dilated or enlarged to maintain its stroke volume [16]. It seems that sustained dilation of the basal segment results in decreased overall contractility of RV. However, after surgical correction, compression to the heart is relieved, and it prevents further dilatation of the basal segment of RV from occurring. This reduces the filling pressure of RV and resistance to maintain the stroke volume and ultimately improving RVEF. Saleh et al. also reported that the RV short-axis diameter decreased, and its long-axis increased in PE patients having lower RVEF than the non-PE counterparts. These findings suggest that the change in the RV anatomy due to PE may alter the pattern of myocardial contraction, mimicking restrictive RV physiology [15]. The present study went a step further and verified the improvement of postoperative RV cardiac indices after surgical correction of PE. In addition, this study used DECT to investigate the relative portion of lung vascular perfusion. DECT is commonly used to understand the diagnosis of pulmonary thromboembolism due to its reliable and non-invasive test protocols [17,18]. As the heart is compressed and distorted due to PE, lung volume and vascular supply are also affected. Therefore, this study tried to elucidate the postoperative change in pulmonary physiology. The change in thoracic cavity could increase the relative size of RUL compared with others, and it could redistribute pulmonary vascular support to each lobe. However, this study was unable to explicate the role of pulmonary vascular redistribution further.

There are several limitations to this study. First, this study was not performed in a prospective, randomized manner, and the number of patients was small. Due to the specific traits of PE, designing a prospective randomized trial is complex. Therefore, we designed a prospective observational study in a single center to get more comparable results. Second, we were unable to measure the improvement of cardiac function based on the varying severities of preoperative PE. Nonetheless, it is important to note that our study did not focus solely on PE patients with cardiopulmonary symptoms; it included all patients who wanted to participate in this study. Finally, this study could not fully explain how the shift in lung volume and perfusion may correlate with cardiopulmonary function improvement. A future study that addresses these weaknesses is warranted. The findings of this study suggest that corrective surgery in patients with PE may improve RV function.

In other words, decreased RV function can be reversed and improved through corrective surgery in PE patients. Although surgical correction of PE results in some changes in lung volume and vascular supply, the exact degree of change was not fully explained in this study. Corrective surgery may be beneficial for improving both cosmetic outcome and cardiopulmonary function in patients with PE.

Funding

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