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ORIGINAL ARTICLE / ÖZGÜN MAKALE

Evaluation of thorax and mediastinum volumes in patients with pectus excavatum by stereological methods

Pektus ekskavatumlu hastalarda toraks ve mediasten hacminin stereolojik yöntemler ile değerlendirilmesi

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ABSTRACT

Background: In this study, we aimed to assess the pre- and postoperative thoracic and mediastinal volumes in patients who received minimally invasive pectus excavatum repair for pectus excavatum.

Methods: Between January 2017 and January 2022, a total of 51 patients (41 males, 10 females; mean age: 15.5±3.5 years; range, 9 to 33 years) who underwent received minimally invasive pectus excavatum repair were retrospectively analyzed. The pre- and postoperative (after bar removal) thoracic computed tomography scans of the patients were evaluated and the mediastinal, lung, and thoracic volumes were calculated using stereological techniques.

Results: The mean pre- and postoperative Haller Index was 3.87±1.32 and 3.28±0.86, respectively. The mean preoperative lung volume-to-preoperative thoracic volume ratio was 79.52±5.15% and the mean postoperative lung volume-to-postoperative thoracic volume ratio was 78.86±6.05%. The mean preoperative mediastinal volume-to-thoracic volume ratio was 20.48±5.15%, and the mean postoperative mediastinal volume-to-thoracic volume ratio was 21.14±6.05%.

Conclusion: Our study results showed no statistically significant increase in the thoracic and mediastinal volumes calculated using stereological methods, while the Haller index values regressed in all patients. These findings suggest that while there may not be a qualitative increase in thoracic and mediastinal volume, there is a quantitative increase in the anteroposterior plane.

Keywords: Chest radiography, computed tomography, correction index, Haller index, pectus excavatum.

ÖZ

Amaç: Bu çalışmada pektus ekskavatum nedeniyle minimal invaziv pektus ekskavatum onarımı yapılan hastaların ameliyat öncesi ve sonrası toraks ve mediasten hacmi değerlendirildi.

Çalışma planı: Ocak 2017 - Ocak 2022 tarihleri arasında pektus ekskavatum nedeniyle minimal invaziv pektus ekskavatum onarımı yapılan toplam 51 hasta (41 erkek, 10 kadın; ort. yaş: 15.5±3.5 yıl; dağılım, 9-33 yıl) retrospektif olarak incelendi. Hastaların ameliyat öncesi ve sonrası (bar çıkartılma sonrası) toraks bilgisayarlı tomografileri değerlendirildi ve stereolojik teknikler kullanılarak mediasten, akciğer, toraks hacimleri hesaplandı.

Bulgular: Hastaların ortalama ameliyat öncesi ve sonrası Haller indeksi sırasıyla 3.87±1.32 ve 3.28±0.86 idi. Hastaların ameliyat öncesi akciğer hacminin göğüs kafesi hacmine oranı ortalama %79.52±5.15 iken, ameliyat sonrası akciğer hacminin göğüs kafesi hacmine oranı ortalama %78.86±6.05 idi. Hastaların ameliyat öncesi mediasten hacminin göğüs kafesi hacmine oranı ortalama %20.48±5.15 iken, ameliyat sonrası mediasten hacminin göğüs kafesi hacmine oranı ortalama %21.14±6.05 idi.

Sonuç: Çalışma sonuçlarımız stereolojik yöntemler kullanılarak hesaplanan toraks ve mediasten hacimlerinde istatistiksel olarak anlamlı bir artış göstermemiş olmakla birlikte, Haller indeks değerleri tüm hastalarda gerilemiştir. Bu bulgular, toraks ve mediasten hacminde niteliksel bir artış olmamakla birlikte, anteroposterior düzlemde niceliksel bir artış olabileceğini göstermektedir.

Anahtar sözcükler: Göğüs radyografisi, bilgisayarlı tomografi, düzeltme indeksi, Haller indeksi, pektus ekskavatum.

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Pectus excavatum (PE) is the most common chest wall deformity characterized by the posterior depression of the middle and lower part of the sternum along with the accompanying costal cartilages.[1] The incidence of PE is approximately 1 in every 400 births, and it predominantly affects males with a ratio ranging from 2:1 to 9:1.[2,3] Physical examination of patients with PE typically reveals a narrow and thin chest, increased dorsal kyphosis, hook shoulder deformity (forward-slumped shoulders), and a poor posture appearance.[4]

A comprehensive history is obtained from patients with PE, including family history. Preoperative photographs are documented while a detailed physical examination is performed.[5] Standard evaluation of patients includes chest computed tomography (CT) or magnetic resonance imaging (MRI), echocardiography (Echo), electrocardiography (ECG), pulmonary function tests, and psychological assessment.

The severity of PE is determined by the Haller Index (HI), calculated as the maximum transverse diameter of the thorax divided by the minimum anteroposterior diameter of the thorax on preoperative chest CT (Figure 1).[6] In a healthy individual, the HI value is 2.5 or less. An HI value of ≥3 indicates a deformity that may require surgical intervention. Therefore, preoperative chest CT is performed to assess the degree of cardiac compression, evaluate thoracic volume reduction, and calculate the HI value.[6,7] Preoperative Echo is also crucial for assessing valve pathologies. Conditions such as mitral valve prolapse, mitral valve insufficiency, and ventricular compression may occur.[8-10]

Surgical repair for PE can be performed using techniques described by Browne[11] and later modified by Ravitch[12] and Welch,[13] or through minimally invasive correction introduced by Nuss et al.,[14] which avoids rib cartilage resection. For patients with mild deformities who prefer non-surgical treatment or have metal allergies, vacuum bell therapy may also be an option.[15]

The primary goal of surgery is to increase the volume of the mediastinal and thoracic cavities, which contain the heart, major mediastinal vessels, and lung tissue, and to relieve the pressure on these organs.[16] Stereological methods, such as the Cavalieri principle, can be used to estimate the volume of biological structures from radiological imaging sections, providing a neutral measurement independent of external factors (e.g., respiratory movement and heart rate). Although Echo can also be used for volumetric assessment, respiratory effects, and heart rate may affect the volume measurements. In contrast, CT examinations, where breathing is suspended, improve the neutrality and reliability of stereological calculations.[17]

In the present study, we, for the first time, aimed to assess changes in the thoracic and mediastinal volumes of patients with PE who underwent minimally invasive PE repair (MIRPE) using pre-treatment and post-treatment examinations.

PATIENTS AND METHODS

This single-center, retrospective study was conducted at Ondokuz Mayıs University Faculty of Medicine, Department of Thoracic Surgery between January 1st, 2017 and January 1st, 2022. Initially, a total of 53 patients who underwent MIRPE and had their bars removed were screened. Inclusion criteria were as follows: having a diagnosis of PE, having undergone MIRPE, availability of pre- and postoperative thoracic CT scans, completion of treatment, and removal of bars. Exclusion criteria were as follows: having thoracic deformities other than PE, having undergone MIRPE for PE but did not have bar removal surgery, undergoing modified Ravitch surgery for PE, patients with incomplete records (pre- and/or postoperative thoracic CT and/or Echo), patients whose bars were removed in less than six months (due to reasons such as metal allergy or scoliosis progression), and patients treated with a vacuum bell. Two of these patients were excluded from the study due to scoliosis progression (n=1) and development of metal allergy (n=1). Finally, 51 patients (41 males, 10 females; mean age: 15.5±3.5 years; range, 9 to 33 years) were

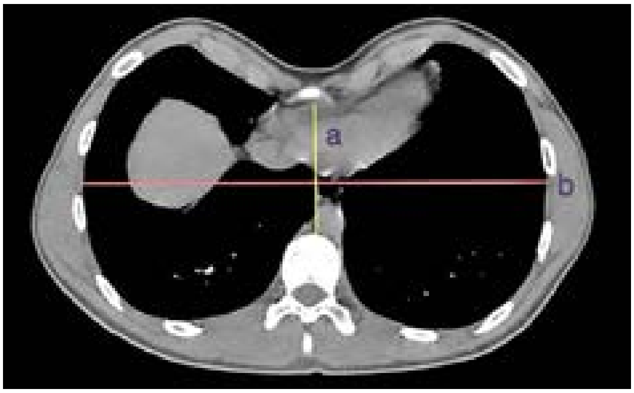

Figure 1. Measurement of the Haller Index.

a: Minimum anteroposterior diameter of the thorax. b: Maximum transverse diameter of the thorax.

included. A written informed consent was obtained from the patients and/or parents of the patients. The study protocol was approved by the Ondokuz Mayıs University Clinical Research Ethics Committee (date: 26/07/2023, no: B.30.2.ODM.0.20.08/351-445). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Demographic data, additional systemic diseases, the number and characteristics of bars and stabilizers used intraoperatively, anesthesia and surgical durations, postoperative complications, lengths of hospital stay, and bar removal times were recorded. Stereological measurements, HI, and correction index (CI) were obtained using pre- and postoperative thoracic CT scans. Preoperative HI and CI values were measured from preoperative thoracic CT scans, and postoperative HI was calculated from postoperative thoracic CT scans. Due to the novel coronavirus disease 2019 (COVID-19) pandemic, respiratory function tests could not be performed and were excluded from the evaluation.

The patients were classified according to their body mass index (BMI) as underweight (<18.5 kg/m^2) or normal weight (18.5 to 24.9 kg/m^2). The HI was calculated based on the formula shown in Figure 1. The CI reflects to the depth of depression of the anterior chest wall, expressed as a percentage of the chest wall depression, in patients requiring surgical correction. To calculate it, a horizontal line is drawn along the anterior edge of the spine, and two measurements are taken. The largest internal anterior-posterior distance (APmax) and the smallest internal anterior-posterior distance (APmin) between the drawn horizontal line and the most anterior part of the chest wall are measured. Therefore, the CI is calculated using the following formula: (APmax-APmin)/APmax × 100 (Figure 2).[18] A CI greater than 10% indicates PE, while a CI greater than 20% suggests a deformity that requires surgical intervention.[7,19]

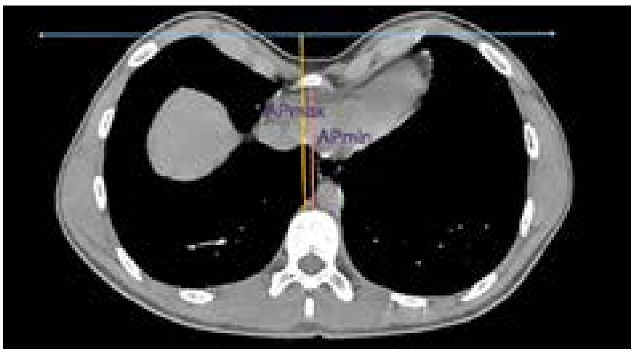

Figure 2. Correction Index Measurement. (APmax-APmin) APmax × 100 APmax (APmax-APmin)×100.

APmax: Largest internal anterior-posterior distance, APmin: Smallest internal anterior-posterior distance.

Stereological calculations

Pre- and postoperative lung volumes were calculated using stereological methods based on the Cavalieri principle applied to thoracic CT images. The number of tomographic slices for each patient was sampled at ratios of 1/3 or ¼, yielding an average of 20 slices.[17] The slice images, saved in Digital Imaging and Communications in Medicine (DiCOM) format, were viewed using the free Horos™ software (The Horos Project; Purview, MD, USA). The thickness of each slice and other relevant information were recorded. The images were exported as separate DiCOM files from the software. These images were, then, opened in the ImageJ software, which is open-source and freely available from the National Institutes of Health, USA. Slice sampling was performed as described above. The surface areas of the slices were measured automatically and semi-automatically using the software's thresholding and manual planimetry options. The internal boundaries of the thoracic cavity were marked manually on the sampled slices using the planimetry method. After marking each slice, the software provided the surface area value in mm^2. The right and left lungs were marked together on each slice using the thresholding method, and their boundaries were automatically traced with the software's magic wand tool. After marking each slice, the software again provided the surface area value in mm^2. The obtained surface areas were multiplied by the slice thickness and sampling coefficient to calculate the volumes of the thoracic cavity and lungs. The volumes were, then, converted to cm^3. The mediastinal volume was calculated by subtracting the lung volumes from the total thoracic cavity volume. Additionally, the lung volume proportion was determined by dividing the lung volume by the total thoracic cavity volume and multiplying by 100. The volume proportion of the mediastinum was obtained by subtracting the lung volume proportion from 100 (Figure 2).

All calculations were performed using templates prepared in Microsoft Excel (Microsoft Corp., WA, USA). Once the data were entered into the templates, the results were generated automatically. Error coefficients for the calculated thoracic cavity and lung volumes were computed for all subjects using literature-based formulas.[20]

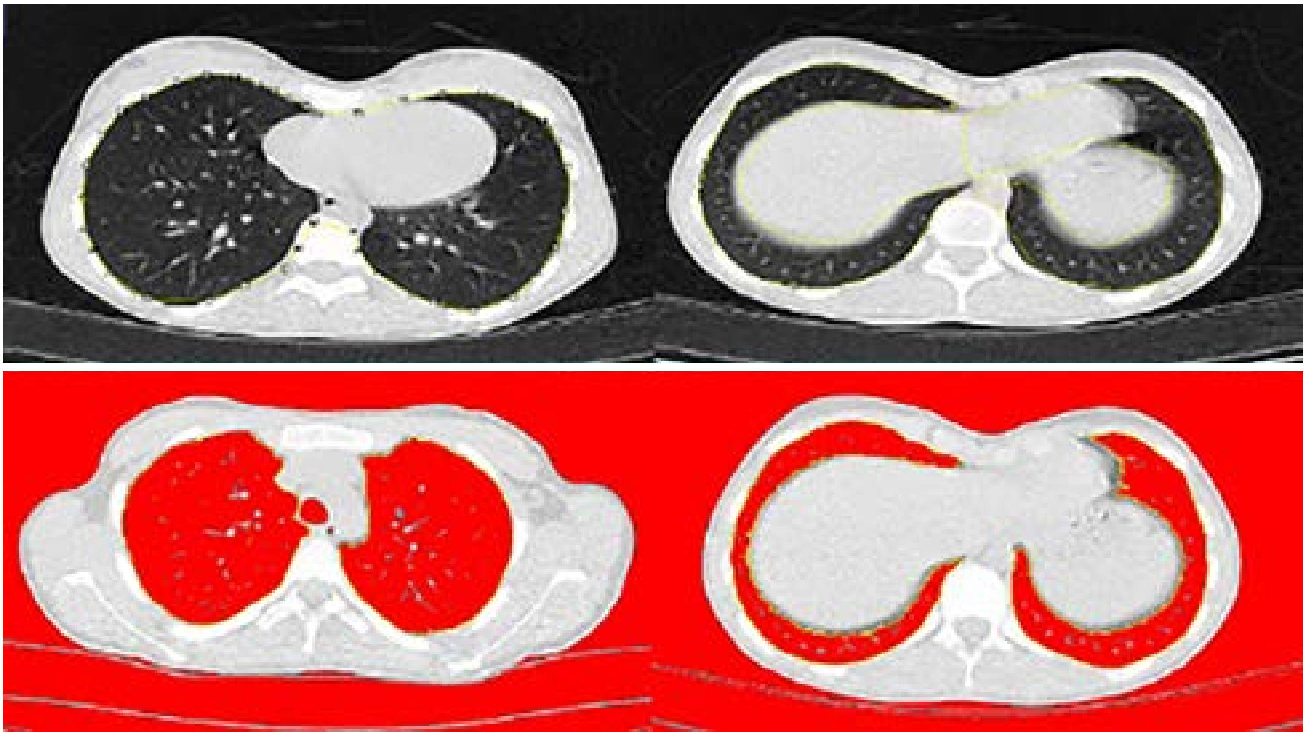

Figure 3. Volume calculation using stereological methods.

Statistical analysis

Statistical analysis was performed using the IBM SPSS version 22.0 software (IBM Corp., Armonk, NY, USA). Descriptive data were expressed in mean ± standard deviation (SD), median (min-max) or number and frequency, where applicable. Differences in measurement values before and after surgery (e.g., postoperative chest volume, PCV-preoperative chest volume, PrCV; postoperative lung volume/chest volume, PLV/PCV)-preoperative lung volume/chest volume, PrLV/PCV) were assessed according to variables such as sex, presence of comorbidities, number of bars, and symmetry-asymmetry by using the Mann-Whitney U test. The relationships between age, height, weight, BMI, HI, CI, bar size, and removal times with changes in pre- and postoperative measurements (e.g., PCV-PrCV, PLV/PCV-PrLV/PCV) were determined using the Spearman correlation analysis. A *p* value of <0.05 was considered statistically significant.

RESULTS

The demographic data and clinical characteristics of the patients included in the study are presented in Table 1.

The pre- and postoperative measurements of chest volume, mediastinal volume, the ratio of lung volume to chest volume, the ratio of mediastinal volume to chest volume, and HI values of the patients are detailed in Table 2.

There were no statistically significant differences in pre- and postoperative measurements between male and female patients, with or without comorbidities (Marfan syndrome), based on the number of bars inserted, deformity symmetry, or the side of asymmetry (p>0.05). However, patients with multiple bars and higher preoperative HI (>3.2) showed a significant reduction in postoperative HI.

There was no statistically significant difference in pre- and postoperative measurements between underweight and normal-weight patients based on BMI status (p>0.05). However, a statistically significant difference was found in the PLH/PCV-PrLV/PrCV and postoperative mediastinal volume (PMV)/PCV-preoperative mediastinal volume (PrMV)/PrCV values based on BMI status. Specifically, the PLV/PCV-PrLV/PrCV values were lower in patients with normal BMI, whereas the PMV/PCV-PrMV/PrCV values were lower in underweight patients (p<0.05). Correlation analysis results are presented in Table 3.

Table 1. Demographic and clinical characteristics of patients (n=51)

Characteristic	n	%	Mean±SD	Range
Age (year)			15.5±3.5	9-33
Sex				
Male	41	80.4		
Female	10	19.6		
Family history of PE	25	49		
Family members with PE deformity				
Father	9	17.6		
Cousin	7	13.7		
Sibling	7	13.7		
Uncle	2	3.9		
Patients with Marfan syndrome	2	3.9		
Preoperative ECHO findings				
Mitral valve disease	16	31.4		
Type of PE				
Symmetric	37	72.5		
Side of asymmetric PE				
Asymmetric	14	27.5		
Average preoperative HI				
Left	11	21.5		
Right	3	5.9		
Average postoperative HI			3.87±1.32	2.38-9.11
Average surgery duration (min)			3.28±0.86	2.18-6.92
Average anesthesia duration (min)			53.43±14.12	30-90
Average hospital stay (day)			73.43±16.23	45-125
Complications	8	9.8	2.47±0.95	1-5
Bar displacement	3	5.9		
Right pleural effusion	1	1.9		
Right pneumothorax	1	1.9		
Time to bar removal after MIRPE (month)			33.43±9.33	18-60
Mortality			None	

SD: Standard deviation; PE: Pectus excavatum; ECHO: Echocardiography; HI: Haller index; MIRPE: Minimally invasive pectus excavatum repair.

Table 2. Preoperative and postoperative measurements of chest volume, mediastinal volume, ratios, and Haller Index

	Preoperative measurement	Postoperative measurement
Variables	Mean±SD	Mean±SD
Haller index	3.87±1.32	3.18±0.86
Error coefficient chest volume	0.89±0.32	1.06±0.47
Error coefficient lung volume	0.91±0.36	1.01±0.37
Chest volume (cm^3)	5023.26±1513.59	5758.51±1395.88
Lung volume (cm^3)	4041.51±1400.10	4584.14±1296.16
Mediastinal volume (cm^3)	981.74±231.70	1174.37±297.57
Lung volume/chest volume	79.52±5.15	78.86±6.05
Mediastinal volume/chest volume	20.48±5.15	21.14±6.05

SD: Standard deviation.

Table 3. Correlation analysis results

	Height	Weight	BMI	Bar size	Bar removal time	HI	CI	PCV-PrCV (cm^3)	PLV-PrLV (cm^3)	PMV-PrMV (cm^3)	PLV/PCV-PrLV/PrCV	PMV/PCV-PrMV/PrCV	Postoperative HI-Preoperative HI
Age	**0.566****	**0.527****	0.359**	**0.589****	0.114	–0.116	–0.114	–0.320*	–0.360**	–0.010	–0.252	0.249	–0.113
Height		**0.728****	0.291*	**0.564****	0.083	–0.127	–0.172	–0.330*	–0.358**	0.013	–0.238	0.240	0.222
Weight			**0.836****	**0.529****	0.042	–0.119	–0.149	**–0.500****	**–0.499****	–0.068	–0.280*	0.282*	0.193
BMI				0.379**	0.039	–0.048	–0.103	**–0.452****	**–0.450****	–0.043	–0.217	0.216	0.096
Bar size					0.255	–0.092	–0.194	–0.128	–0.204	0.173	–0.163	0.165	0.071
Bar removal time						–0.069	–0.130	–0.005	–0.077	0.188	–0.196	0.194	–0.016
HI							**0.838****	0.019	0.056	–0.190	0.262	–0.265	**–0.549****
CI								0.046	0.059	–0.188	0.192	–0.192	**–0.583****
PCV-PrCV (cm^3)									**0.964****	0.307*	**0.496****	**–0.493****	–0.219
PLV-PrLV (cm^3)										0.114	**0.668****	**–0.664****	–0.242
PMV-PrMV (cm^3)											**–0.496****	**0.498****	0.195
PLV/PCV-PrLV/PrCV												**–1.000****	–0.366**
PMV/PCV-PrMV/PrCV													0.367**

BMI: Body mass index; HI: Haller index; CI: Correction index; PCV: Postoperative chest volume; PrCV: Preoperative chest volume; PLV: Postoperative lung volume; PrLV: Preoperative lung volume; PMV: Postoperative mediastinal volume; PrMV: Preoperative mediastinal volume; * p<0.05; ** p<0.01; *** p<0.001.

DISCUSSION

In patients presenting to the outpatient clinic with chest wall deformities, after the diagnosis of PE is made through medical history and detailed physical examination, low-dose, non-contrast thoracic CT is performed to determine the treatment modality and to calculate indices for the evaluation of the severity of the deformity. The most commonly used index is the CT-based HI with a value greater than 3.25 indicating children who meet the surgical criteria.[6] In the present study, the mean preoperative HI was 3.87±1.32, and the postoperative HI was 3.17±0.86. After a sufficient period following MIRPE and bar removal, the HI decreased, and the differences were statistically significant. In a study by Li et al.[21] involving 259 patients with a median age of 15.54 years, the HI improved in all patients following MIRPE. Similarly, in a study by Kuyama et al.[22] involving 173 patients, the mean postoperative HI was found to be higher than the preoperative HI (preoperative HI: 2.46±0.35, postoperative HI: 2.72±0.52), which was attributed to the patients' younger mean age of 6.1±1.3 years.

The HI has been defined as the gold standard for determining the severity of PE. However, some researchers have suggested that this index may not accurately reflect the severity of PE in patients with inconsistencies in the anteroposterior and mediolateral dimensions of the chest wall.[7] In patients with asymmetric deformities, considering the rotation of the manubrium sterni, this theory may be accurate. During our study, we encountered difficulties in accurately calculating the HI in these patients.

Since the HI compares the degree of pectus deformity with the width of the chest cavity, the results may be confounded in patients with wide or narrow chests. St Peter et al.[7] defined the CI as a new tool to more accurately assess the severity of PE and the potential degree of repair. While the HI is well correlated with CI in pectus patients with standard chest wall dimensions, it is inconsistent in non-standard chests. In this study, the mean preoperative CI was 28.14±11.43, showing a strong positive correlation (r=0.838) between HI and CI. Moreover, in line with CI reflecting the potential degree of repair, a statistically significant, inverse and moderate relationship was observed between CI and postoperative/preoperative HI.

Researchers such as Welch,[13] Hümmer and Willital,[23] Backer et al.,[24] and Haller et al.[6] developed indices to measure deformity severity and/or provide a more objective comparison between pre- and postoperative periods. However, all of these measurements rely on two-dimensional images in two planes. In our study, we attempted to identify volume increases in the thoracic wall, mediastinum, and lung volumes in a three-dimensional and unbiased manner, guided by these indices. To achieve this, we used the Cavalieri principle, a stereological method, to measure volumes from CT slices that allow three-dimensional imaging of organs and structures. In this context, our study is the first in the literature.

In a study by Chu et al.,[25] the preoperative HI was the highest in the preschool age group (<6 years) with a mean of 4.5±2.0, while the mean postoperative HI was the lowest at 2.3±0.3. The change in postoperative HI showed the greatest difference (–2.2±1.9). Both males and females showed lower postoperative HI values and lower HI values after bar removal, with no statistically significant differences between the sexes. Similarly, Mortellaro et al.[26] compared pre- and postoperative HIs in 262 patients using thoracic CT scans and found no association between HI and factors such as age, surgery duration, postoperative bar infection, and length of hospital stay. A minimal correlation was observed only between HI and the development of postoperative pneumothorax. In our study, no statistically significant differences were found in the pre- and postoperative measurement values before and after surgery with respect to age or sex. Similarly, there were no statistically significant differences in measurement values before and after surgery with the presence of Marfan syndrome as a comorbidity. One possible reason for this lack of significance could be the small number of patients with Marfan syndrome (n=2).

In a study by Htut et al.[27] involving 272 patients, the relationship between BMI and HI changes following MIRPE was evaluated. They found that, after bar removal, BMI, height, and weight increased significantly in adult patients, particularly in young males and those with more severe deformities. In our study, comparisons of volume and ratio were made according to BMI status. Statistically significant differences were observed for PLV/PCV-PrLV/PrCV and PMV/PCV-PrMV/PrCV values based on BMI. In particular, the PLV/PCV-PrLV/PrCV value was lower in patients with normal BMI, whereas the PMV/PCV-PrMV/PrCV value was lower in underweight patients. This finding suggests that, in underweight patients, the mediastinal volume increased more, while in normal-weight patients, the lung volume increased more. This may be due to the greater resistance to the pushing force of the bar in patients with more extra-thoracic muscle and fat tissue.

In the current study, we evaluated the changes in thoracic and mediastinal volumes following MIRPE using stereological methods. Unlike most studies in the literature, which typically use two-dimensional imaging techniques, this study utilized three-dimensional volume measurements. The contribution of this study to the literature lies in providing a more precise assessment of the changes in thoracic and mediastinal volumes after MIRPE, allowing for a better understanding of the anatomical and functional outcomes of surgical interventions. This also represents a significant contribution to clinical practice.

One of the main limitations to our study is the difficulty in accurately calculating the HI in patients with asymmetric deformities. The single-center, retrospective design with a relatively small sample size may have also limited our ability to interpret our results with certainty and provide wider generalizations. Further multi-center, large-scale, prospective studies are needed to confirm these findings.

In conclusion, the current and most effective treatment of pectus excavatum is minimally invasive pectus excavatum repair. The primary goal of surgery is to expand the thoracic and mediastinal volumes, thereby alleviating pressure on intramediastinal and intrathoracic organs such as the heart, lungs, and major vessels and improving their functional capacities. This not only achieves the main surgical goal of cosmetic correction, but also helps prevent potential early cardiopulmonary complications in the future. Our study results showed no statistically significant increase in the thoracic and mediastinal volume values calculated using stereological methods, while the Haller index values regressed in all patients. This finding suggests that while there may not be a qualitative increase in thoracic and mediastinal volume, there is a quantitative increase in the thoracic and mediastinal volumes in the anteroposterior plane. In particular, the lateral plane volume, which is increased due to the posterior pressure of the deformity, is redistributed into the anteroposterior plane as the bar elevates the sternum. Further studies are still warranted to draw more reliable conclusions on this subject.

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