7 Indexes for Pectus Deformities

Marcelo Martinez-Ferro

Abstract

A thoracic index is a formula used to qualify or quantify a thoracic deformity and in some cases, to define strategies within treatment. It is also a diagnostic tool used historically to assess the severity of the defect. There is no definition, classification, or consensus in the literature on which thoracic index is the gold standard. There are also no guidelines regarding cut-off values. This chapter is an effort to put all this together, starting by defining thoracic indexes, proposing a classification and describing them in detail for the first time. The main objective is to find out which are the most commonly indexes used by chest wall malformation experts worldwide, and why. For this reason the present chapter includes a web-based survey made to the aforementioned experts in order to review this issue in detail. Since there is currently no thoracic index without limitations, perhaps the perfect index is a mathematical combination of several different indexes. Perhaps it is one single index still to be discovered. This is the first step to search for a universal thoracic index for surgical – decision making.

Keywords

Thoracic Index • Haller Index • Pectus Excavatum • Severity • Surgery

Introduction

There is presently no definition of "thoracic index" or consensus in the literature on which one is the gold standard. There are also no guidelines regarding cut-off values. Assessment of patients and the process of surgical-decision making vary considerably among chest wall malformations experts worldwide [1–3]. Moreover, even though thoracic indexes can be used to evaluate any chest wall malformation they are commonly employed to study Pectus Excavatum (PE) patients. The objective of this chapter is to review this topic and to report the results and observations from a web-based survey.

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Definition

Basically a thoracic index is formula employed to characterize a set of data obtained from thoracic (basically anterior chest wall and cardiac) measurements. It is a diagnostic tool used historically to assess the severity of the deformity. A thoracic index comprises a cut-off point, that is, a limit at which expectant treatment for a pathology, as PE, is or is not longer applicable. Additionally, it allows surgeons to define strategies within treatment. Thoracic indexes vary with age, gender, body mass, and morphology (cup, saucer, grand canyon, and other shape depressions), among other factors [2–7].

Usefulness of Thoracic Indexes

1. To assess the severity of the defect
2. To establish a cut-off point for treatment indication
3. To define treatment strategies
4. To quantify postoperative changes in the shape of the chest

Recent thoracic indexes have been focused not only on the severity of the defect as aforementioned, but on characteristics of the sternum, the deformity, and the impact PE has on the patients' cardiopulmonary function [8, 9].

Type of Thoracic Indexes

Diagnostic Indexes

1. Clinical Indexes
2. Chest-X-Ray Indexes
3. Chest-CT-Scan Indexes
4. Chest and Cardiac MRI Indexes
5. Other Indexes

Subtype of Thoracic Indexes

Assessment Indexes

1. Sternal Indexes
2. Severity Indexes
3. Deformity Indexes
4. Cardiac Indexes

Classification

There is presently no classification of thoracic indexes. In an effort to organize the large amount of diagnostic and assessment indexes in existence until date, the following classification is proposed (Table 7.1).

It must be pointed out however that, even though cardio-pulmonary function tests are rarely indicated for surgical decision making, evaluation of the impact of the sternal depression on the lung and heart are helpful for achieve a full diagnosis of the defect, deal with health insurance companies and enable the patient and family understand that the PE is not only an aesthetic problem.

Validation

Validation is the confirmation of the experience or judgment of one author by another and is achieved by repeating another author's work and reaching the same results. The same materials, methods, inclusion and exclusion criteria have to be used. Publishing the validated results is encouraged to reinforce the author's original experience and findings. The Haller Index cut-off point of 3.25 used for surgical indication, for example, has never been validated by other authors, even though a great deal of chest wall malformation experts use it routinely in their practice. Although a huge variety of indexes have been described in the literature, only few authors have validated some of them. An example of validation is the recent publication of Poston et. al. in which the Correction Index described by St. Peter et al. was analyzed obtaining similar results than those obtained by the original authors.

Description

The most frequently reported thoracic indexes will be hereby described.

Table 7.1 Proposed classification of the most commonly reported thoracic indexes

Type	Subtype	Thoracic indexes
Diagnostic indexes	Assessment indexes	Most commonly reported indexes
Clinical		Anthropometric Index [5, 10–12]
Chest X-ray	Sternal	Vertebral Index [7, 10, 13–16]
		Welch Index [17, 18]
		Haje Body Manubrial Index [2]
		Haje Body Manubrial Xyphoid Index [2]
	Severity	Chest-X-Ray Haller Index [19–21]
	Deformity	Configuration Index [7]
		Frontosagittal Index [16]
Chest CT scan	Sternal	Haje Width Length Index [1]
	Severity	Haller Index [22–24]
		Modified Haller Index In expiration [24, 25] For carinatum [7]
		Correction Index [19, 26]
	Deformity	Asymmetry Index [6, 27–29]
		Vertebral Index [28]
		Frontosagittal Index [28]
		Steepness Index [27]
		Excavatum Volume Index [27]
		Depression Index [28, 30]
		Eccentricity Index [28, 29]
		Unbalance Index [28]
		Flatness Index [29]
		Circularity Index [29]
	Cardiac	Cardiac Compression Index [31]
		Cardiac Asymmetry Index [31]
		Modified Cardiac Compression Index [24]
Chest and cardiac MRI	Sternal, severity, deformity and cardiac	All the aforementioned
		Cardiac MRI Indexes [32–37, 45]
Other[a]		Stress cardiac ultrasound [38]
		Pletismography [39]
		External body scanner Indexes [38, 40]

[a]These thoracic indexes will not be assessed in the current chapter

Clinical Indexes

Anthropometric Index

As stated by its authors, the **A**nthropometric **I**ndex (**AI**) is a quickly administered and low-cost clinical assessment tool, which does not induce any adverse effects and is not vulnerable to environmental influences. The A and B clinical measurements are carried out with the patient in a horizontal supine position on a flat table parallel to the floor during deep inhalation. The A measurement is defined as the largest anteroposterior diameter at the level of the distal third of the sternum, and the B measurement, as the largest depth at the same level.

The AI for PE is calculated by dividing B by A (Fig. 7.1) [5]. The AI cut-off point for PE pre- and postoperatively is 0.12.

Anthropometric Index = B/A

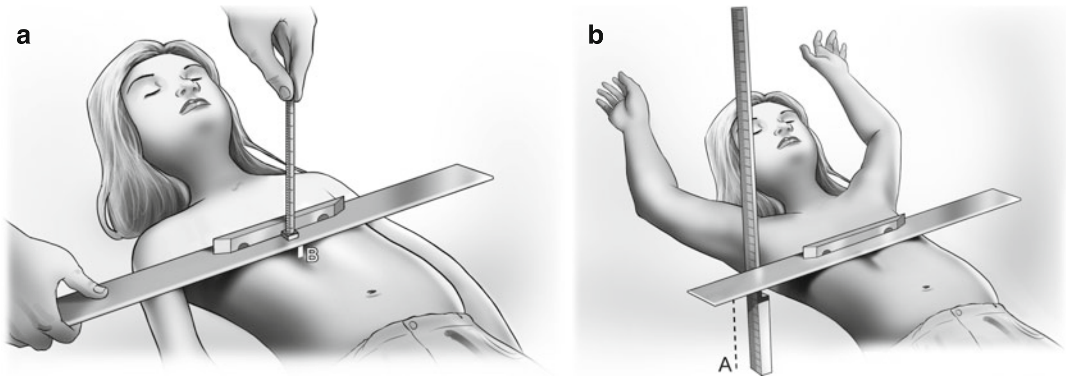


Fig. 7.1 Schematic representation of a PE patient for the calculation of the **Anthropometric Index**. (**a**) measurement of the anteroposterior distance during deep inhalation at the distal third of the sternum. (**b**) measurement during deep inhalation at the greater depth, at the distal third of the sternum. The instruments used were: an articulated square, a rigid ruler coupled to a level (the measuring device), a pinned limiting device and a conventional ruler

The case series presented by Rebeis et al. [10] exhibited significant difference between male and female patients. The authors believed that the breasts accounted for this difference because measurements A and B were obtained using gauging devices that run across the chest. This belief is supported by no difference being found between male and female preteen subjects (3–10 years), when the breasts have not yet been developed. Authors such as Knutson [11] and Horst et al. [12] endorse the AI.

Chest X-ray Indexes

Because direct measurements are subject to variations in age, height, and body mass, radiographic indexes were also developed.

Vertebral Index

Authors such as Rebeis et al. [10], Welch [17], Backer et al. [13], Hummer and Willital [15], Haller et al. [22], and Derveaux et al. [7] formulated individual indexes to quantify the severity of the deformity and/or to enable the comparison between preoperative and postoperative results more objectively. All of them have in common that their indexes relate the approximation of the sternum to the spinal column. The **V**ertebral **I**ndex (**VI**) is calculated from a lateral thoracic radiography. It is defined as the ratio between the sagittal diameter of the vertebral body (BC) and the sagittal anteroposterior diameter of the posterior side of the sternum until the posterior side of the vertebral body (AC). The **L**ower **V**ertebral **I**ndex (**LVI**) is calculated at the xiphisternal junction [7, 10], whereas the **U**pper **V**ertebral **I**ndex (**UVI**) is calculated at the sternomanubrial junction [7].

Rebeis et al. [10] found that the LVI cut-off point for PE patients pre-operatively is within the means published by Derveaux et al., that is, 0.292 ± 0.067 (Fig. 7.2). Derveaux et al. [7] proposed three Chest-X-Ray indexes. The LVI (age dependent) was measured at the xiphisternal junction and calculated by BC/AC. The UVI (age independent) was measured at the sternomanubrial junction and calculated by EF/DF. The **Con**figuration **I**ndex (**ConI**) was the result of the ratio between DE/AB where DE and AB are the sagittal anteroposterior diameter of the back side of the sternum to the front side of the vertebral body, at the xiphisternal and sternomanubrial junctions, respectively. The ConI was particularly valuable in patients with complex PE, often with axial sternal rotation and/or scoliosis (Fig. 7.2). Mean pre-operative UVI was equal to 0.235 ± 0.045. Mean pre-operative ConI was equal to 1.175 ± 0.214. The results obtained regarding LVI were compatible

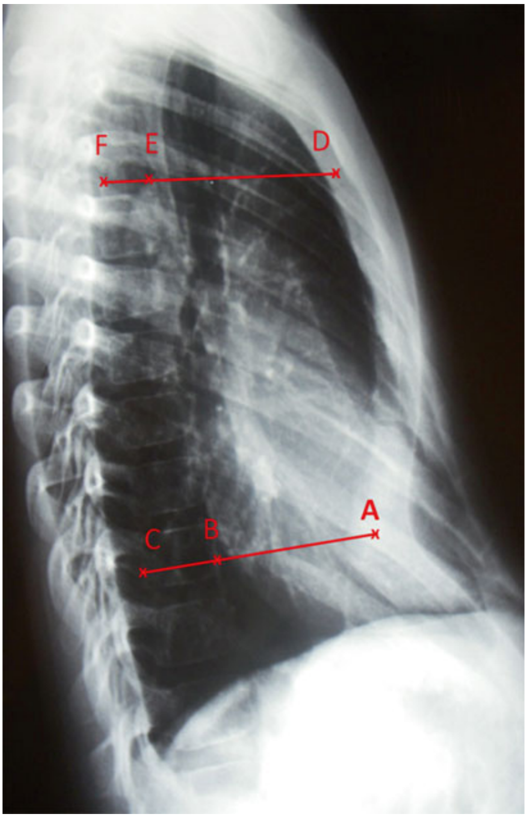


Fig. 7.2 Lateral Chest-X-Ray of a PE patient. Note Rebeis et al. and Derveaux et al. measurements to calculate the **Lower Vertebral Index** at the xiphisternal junction. *BC* = sagittal diameter of the vertebral body and *AC* = sagittal anteroposterior diameter of the back side of the sternum to the back side of the vertebral body. Derveaux et al. also measure the **Upper Vertebral Index** at the sternomanubrial junction. *EF* = sagittal diameter of the vertebral body and *DE* = sagittal anteroposterior diameter of the back side of the sternum to the back side of the vertebral body. The **Configuration Index** is the ratio between the sagittal anteroposterior diameter of the back side of the sternum to the front side of the vertebral body at the xiphisternal (*DE*) and sternomanubrial (*AB*) junctions

with those of Ohno et al. who expressed results as a percentage ratio. The pre-operative cut off point for LVI > 27 [16].

Lower Vertebral Index = BC/AC
Upper Vertebral Index = EF/DF
Configuration Index = DE/AB

Frontosagittal Index

According to Ohno et al. the **F**ronto **S**agittal **I**ndex (**FSI**) is the percentage ratio between maximum internal transverse diameter (T) and minimum sagittal diameter of the chest, measured from the anterior surface of the vertebral body to the nearest point on the sternal body (D).

The authors concluded that the LVI decreased whereas the **FSI** increased significantly post-operatively (Fig. 7.3). They suspected that the abnormal post-operative indexes were the result of thin and flat chests, because of the short sagittal diameter of the thoracic cage, even though the sternum was adequately elevated and PE patients were satisfied with the cosmesis. The pre-operative cut off point for FSI < 29 [16].

Lower Vertebral Index = (B/A) × 100
Fronto Sagittal Index = (D/T) × 100

Welch Index

In 1958, Welch reported a technique for the correction of PE that emphasized total preservation of the perichondrial sheaths of the costal cartilage, preservation of the upper intercostal bundle, sternal osteotomy and anterior fixation of the sternum with silk sutures [17]. By the year 1988, Shamberger and Welch, had surgically corrected 704 PE patients with the same technique. Severity of the deformities was assessed on a scale 1–10 based on a series of measurements made from chest-x-rays (Fig. 7.4) [18]. According to the authors, surgical repair is recommended for PE patients beyond infancy with an inflexible deformity and a severity rating **W**elch **I**ndex (**WI**) of ≥5.

By calculating the:
1. **Depression ratio** (**DR**) = D_1/D_2,
2. **Deformity Grade** (**DG**) = (1−DR) × 10 and the,

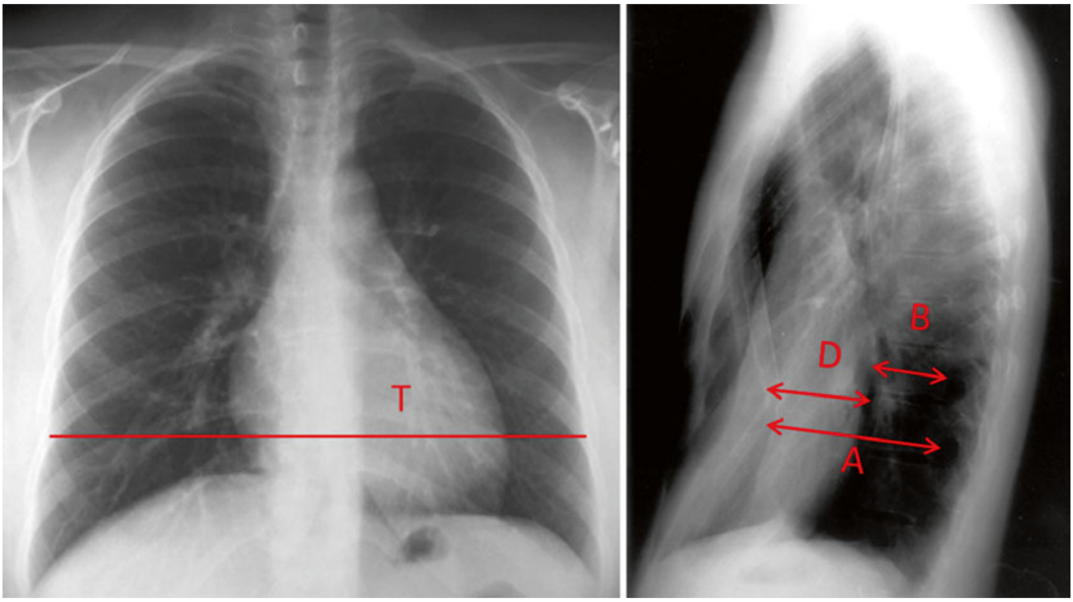


Fig. 7.3 PA and lateral Chest-X-Rays of a PE patient. **Lower Vertebral Index**: percentage ratio between minimum sagittal diameter of the chest measured from the posterior surface of the vertebral body to the nearest point on the sternal body (*A*) and the sagittal diameter of the vertebral body at the same level. (*B*) **Fronto Sagittal Index**: percentage ratio between maximum internal transverse diameter (*T*) and minimum sagittal diameter of the chest, measured from the anterior surface of the vertebral body to the nearest point on the sternal body (*D*)

3. **Cardiothoracic Ratio** = maximal horizontal cardiac diameter/maximal horizontal thoracic diameter (inner edge of ribs/edge of pleural) multiplied by 100. It is measured form a PA Chest-X-Ray. Normal values are <50 %.

The Welch Index is equal to:

– DG + 0.5 if Rib angle (Ø) > 25°

and/or

DG + 0.5 if the Cardiothoracic ratio >50 %

Haje Body Manubrial Index This sternal index has been proposed by Haje et al. It is obtained from a lateral chest X-ray. To calculate it, the length of the manubrium and body of the sternum are measured in centimeters. A ratio resultant of the division of the length of the ossified body (B) by the length of the ossified manubrium (M) is called the **B**ody **M**anubrium (**BM**) Index [2] (Fig. 7.5). It cannot be obtained when sternal segments are fused.

Body Manubrium Index = B/M

Haje Body Manubrium Xyphoid Index

This sternal index has also been proposed by Haje et al. It is obtained from a lateral Chest-X-Ray when ossification of the xyphoid process (X) is observed. A new ratio, representing the distance in centimeters from the top of the body to the bottom of the xyphoid process (BX) divided by the length of the manubrium (M), is obtained and called the **B**ody **M**anubrium **X**yphoid (**BXM**) Index (Fig. 7.5) [2].

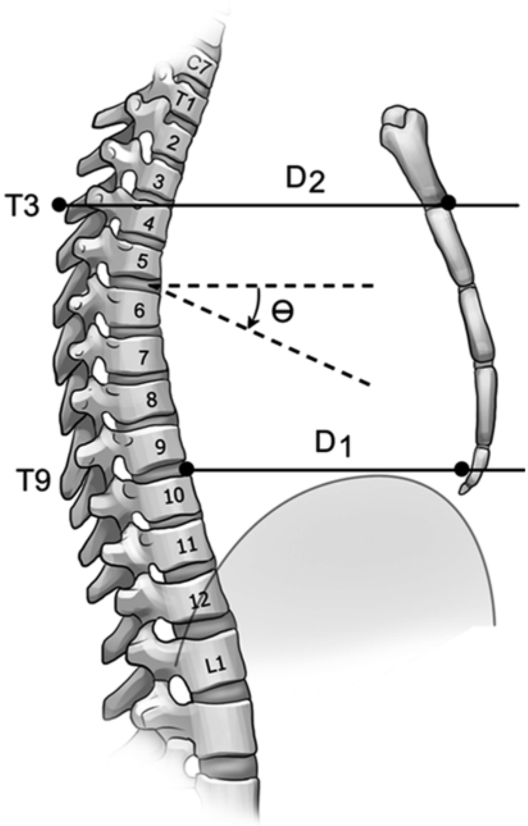


Fig. 7.4 Welch's method of grading severity of the deformity (Welch Index) uses the distance from the anterior surface of the spine at T-9 to the posterior surface of the sternum (*D-1*), over the distance from the spinous process of T-3 to the angle of Louis (*D-2*). Additional 0.5 is added if the rib angle (*Ø*) is greater than 25° or the cardiothoracic ratio is >50 %

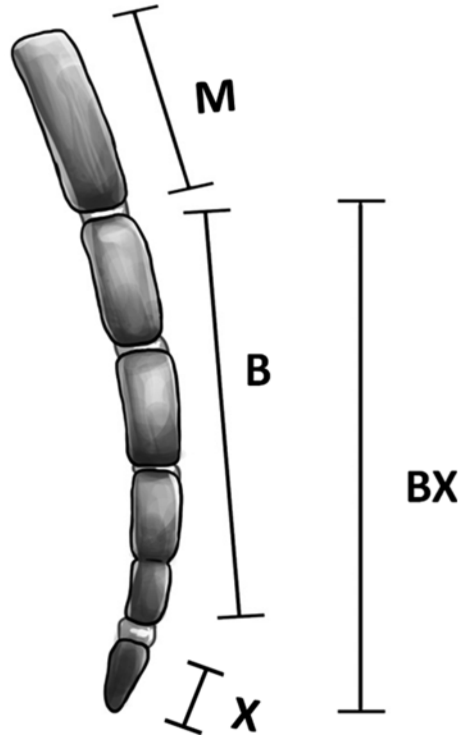


Fig. 7.5 Diagram of the measurements done on the lateral view of the sternum. (*M*) Manubrium length; (*B*) Body length; (*BX*) Body-Xyphoid distance. A lateral radiograph of a normal 11-year-old patient was used as a model

Body Manubrium Xyphoid Index = BX/M

The sternal body in controls is slightly more than twice the length of the manubrium. The cutoff point for the BM Index is 2.16 and for the BMX Index is 2.73. Lower BM values depict shorter sternal bodies.

The study originally aimed to determine the influence of sternal growth on the development of pectus deformities and correlate imaging studies with clinical aspects of different types of deformities. Although it was not Haje's main objective, when considering the BM and the BMX sternal indexes from a surgical point of view, these indexes might be useful to define surgical strategies as for example to predict the number of pectus bars needed for a Nuss procedure by correlating sternal length, age and thoracic elasticity.

Chest-X-ray Haller Index

The **H**aller **I**ndex (**HI**) will be explained in detail further in this chapter. It derives from dividing the greater transverse diameter (the horizontal distance of the inside of the ribcage) by the

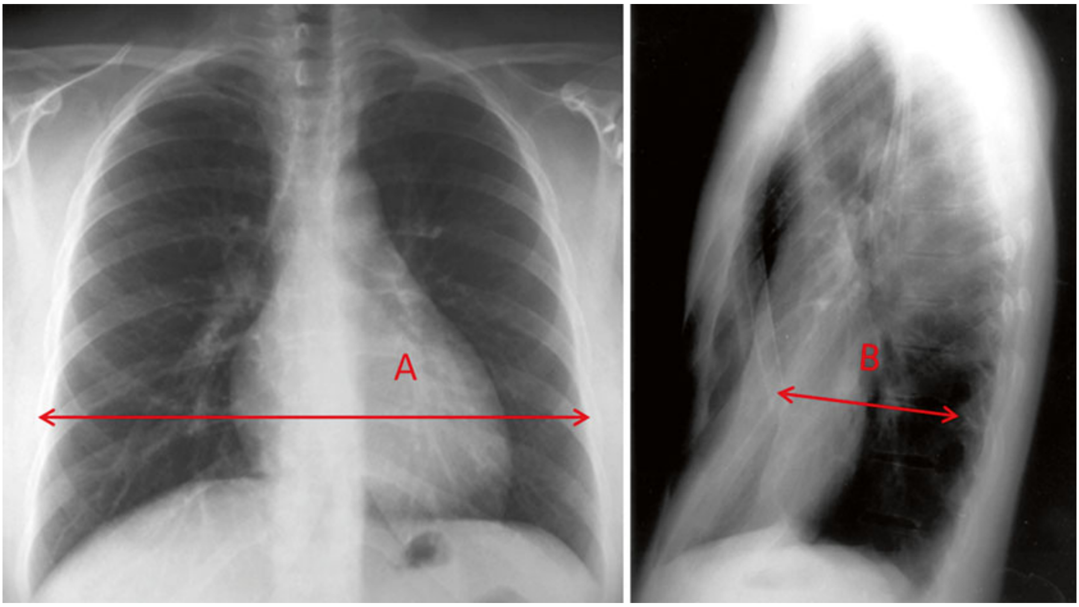


Fig. 7.6 **Chest-X-Ray Haller Index** measurement on two-view chest radiography. (*A*) The point of most posterior projection of the sternum is identified, and the distance between that segment and the anterior aspect of the corresponding vertebra is measured. (*B*) The lateral diameter is measured at the vertebral body level on the anteroposterior view

anteroposterior diameter (the shorter distance between the vertebrae and the sternum).

Poston et al. determined PE severity from Chest-X-Rays, instead of Chest CTs, to minimize radiation exposure of PE patients. Authors found a strong correlation between HIs calculated from Chest-X-Rays (Chest-X-Ray HIs) and those by Chest CT Scans. Both HIs demonstrated good inter-rater reliability. Nonetheless, even though the sensitivity of Chest-X-Rays in diagnosing severe PE (Chest CT HI$\geq$3.2) resulted high, specificity was less convincing. But when using a cut-off point for Chest-X-Ray HIs of 3.75 or greater, combined specificity resulted quite high (0.96). They finally suggested using Chest CT Scans as a confirmatory test for Chest- X-Ray HIs between 3.2 and 3.75 [19].

According to Khanna et al. [20], Chest-X-Ray HI correlates strongly with Chest CT HI, has good inter-observer correlation, and a high diagnostic accuracy for pre-operative evaluation of PE. Authors suggest that a Chest CT is not required for pre-operative evaluation of PE, and a two-view Chest-X-Ray is sufficient enough for preoperative imaging of the defect.

Mueller et al. [21] measurements, calculated from preoperative Chest-X-Rays yielded HIs equivalent to those taken from Chest CT Scans. Authors postulated that the replacement of preoperative Chest CT by radiographies would reduce unnecessary exposure to radiation in children with asymptomatic PE. They believe this is particularly desirable because radiation exposure may have long-term side effects in growing children that range from long bone growth derangements to fatal malignancies. When in doubt, a Chest CT Scan could be indicated for the preoperative evaluation (Fig. 7.6).

Chest-X-Ray Haller Index = A/B

Chest Scan Indexes

Haje Width Length Index

This index was proposed by Haje et al. from coronal CT Scans, traced out on a schematic representation of the anterior chest wall. The **W**idth **L**ength **I**ndex (**WLI**) is calculated by dividing

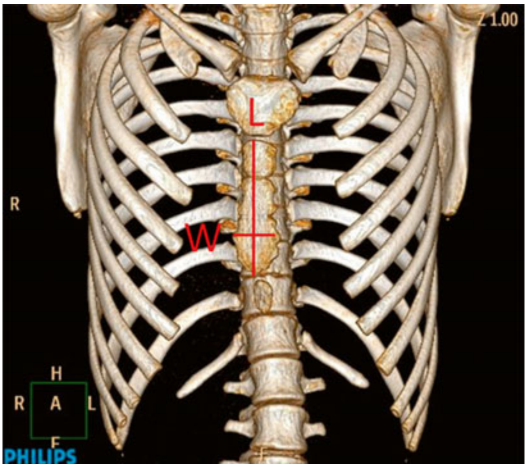


Fig. 7.7 Lines *W* (widest length of the ossified sternal body) and *L* (longest length of the ossified sternal body), are used for the study of the WL index in coronal CT Scans. The **Width Length Index** is calculated by the division of W by L

the maximum width of the ossified sternal body by its length (Fig. 7.7). This implies higher WLI indexes for wide sternal bodies, with possible connotations for the prognosis and treatment of different types of pectus deformities [1]. The mean WLI Index for controls is 0.420. The mean WLI Index for PE patients is >0.446.

Width Length Index = W/L

Sternal Depression Index

The **S**ternal **D**epression **I**ndex (**SDI**) is the ratio between the maximal internal sagittal diameter of the left side of the chest (C) and the minimal distance between the anterior surface of the vertebral column and the posterior border of the deepest portion of the sternum (B).

The vertical distance between the higher and lowest point of the anterior chest wall (A) is a measure of the sternal depression.

Chu et al. [30] reported that the average depth of depression of the sternum (A) was 21 ± 7 mm whereas the SDI was 2.7 ± 1.4. When the SDI was arbitrarily used to classify the severity of sternal deformity, mild sternal deformity was associated to a SDI < 2.4; moderate sternal deformity was

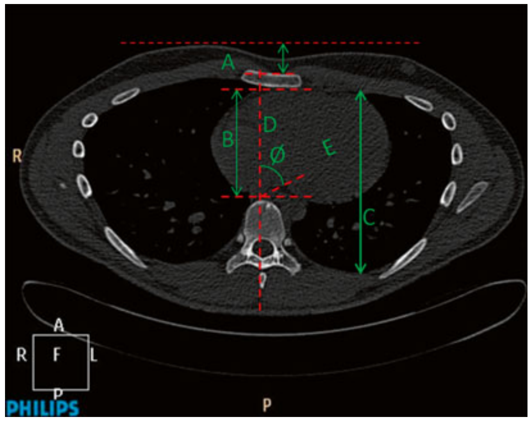


Fig. 7.8 Chest CT Scan showing measurements to calculate the depth of sternal depression (*A*), **Sternal Depression Index** (*C*/*B*), and cardiac rotation angle (*Ø*). *D* = sagittal line from anterior border of the vertebral body and line from anterior border of vertebral body (*E*)

associated to a SDI between 2.4 and 2.9; and severe sternal deformity was associated to a SDI index >2.9 (Fig. 7.8). As the depression index increased, the cardiac rotation angle (Ø) increased with a correlation coefficient of 0.75.

Haller Index

The **H**aller **I**ndex (**HI**), described in 1987 by Dr. Haller J, Dr. Kramer and Dr. Lietman, is a mathematical relationship, usually measured by chest CT scans [22]. As aforementioned, HI derives from dividing the transverse diameter (the widest horizontal distance of the inside of the ribcage) [T] by the anteroposterior diameter (the shorter distance between the vertebrae and the sternum) [A] (Fig. 7.9) [23].

Haller Index = T/A

Despite several issues that will be discussed further, the HI remains a useful tool in judgment of operative indication. The cut-off point for PE patients is >3.25 [22].

The HI has been chosen as the gold standard for the majority of chest wall malformation experts. Presumably because it is easy to measure, and because surgeons and radiologists are

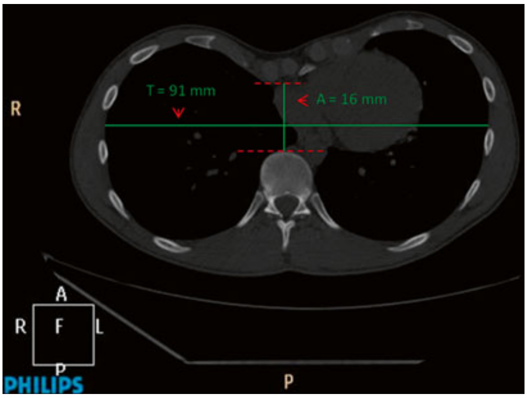


Fig. 7.9 CT axial image: Calculation of the *Haller Index* = 91 mm/16 mm = 5.68. The sternum is so severely depressed that it is 1.6 cm from the anterior portion of the vertebra

used to calculate and interpret it. Moreover, it has a high inter-observational reliability as demonstrated by Lawson et al. [41] Nonetheless, it is thoroughly documented that the HI has several limitations (Table 7.2).

To start with, there is no convincing evidence regarding it provides accurate information to guide surgical correction of PE. Its cut-off point is quite variable among authors. Daunt et al. [4] for instance proposed an upper limit of 2.7, Khanna et al. [20] of 3.2, Kilda et al. [43] of 3.1 whereas most chest wall malformation experts adopt a cut-off point equal or greater than 3.25. In spite of this, as Lawson et al. [41] published, there is a considerable variability among medical practitioners in determining the HI depending on how the images are chosen and how measurements are taken from the chosen images. Secondly, the HI might be unreliable since it varies with age, gender [4, 5], thoracic shape [2, 5], and whether it is done in inspiration or expiration [30]. Thirdly HI is unpractical for surgical – decision making as it does not consider asymmetry [24], percentage of sternal and costal depression [24], cardiac compression or cardiac asymmetry [41, 44]. Also results from controls and PE patients overlap between each other [26]. While width serves as a surrogate for comparing dimensions of the chest, it does not depict the position of the sternum relative to the anterior ribcage. A wide chest increases HI whereas a narrow chest decreases HI regardless of the severity of the

Table 7.2 Limitations of the Haller Index

Problems with the Haller Index (thoroughly documented in the literature)	
Fairness (for patients and surgeons)	3.25 cut-off point for surgical indication is no longer a good discriminator between PE patients and controls [4, 20, 28, 41]
	Bares no conclusive relationship with the aesthetic complaints observed [24, 41]
	Variation with thoracic shape [2, 5, 41]
	Variation with age and gender [4, 5]
	Variation with inspiration/expiration [24]
	Depends on chest width which results in overlapping between controls and PE patients [26]
Practicity	Does not consider asymmetry [27–29, 41–44]
	Does not consider cardiac compression [29, 31, 38]

PE [24]. HI bares no conclusive relationship with the aesthetic complaints observed. For instance, the patient in (Fig. 7.10) clearly has a PE. But when calculating his HI it is equal to 3.24. St. Peter et al. proposed the Correction Index (CI), a novel thoracic index, which is independent of chest width and assesses the percentage of chest depth [26]. The CI will be described ahead in this chapter.

Modified Haller Indexes

The Modified Haller Indexes result from changes made to the HI.

Haller Index in Expiration

Chest wall diameters vary with breathing and these variations may modify the **H**aller **I**ndex in **Ex**piration (**HI-Ex**) values and surgical indications [25]. Albertal et al. found that the antero-posterior diameter values vary from end-inspiration to end-expiration, and correspond to significant changes (29.6 %) in HI values (Fig. 7.11) [24]. Their study showed that HI was more severe at end-expiration than at end-inspiration, leading to an increase in surgical candidacy.

Haller Index for Carinatum

The **H**aller **I**ndex for **C**arinatum (**HI-Car**) is a kind of "reverse" HI described by Poncet et al. [40]

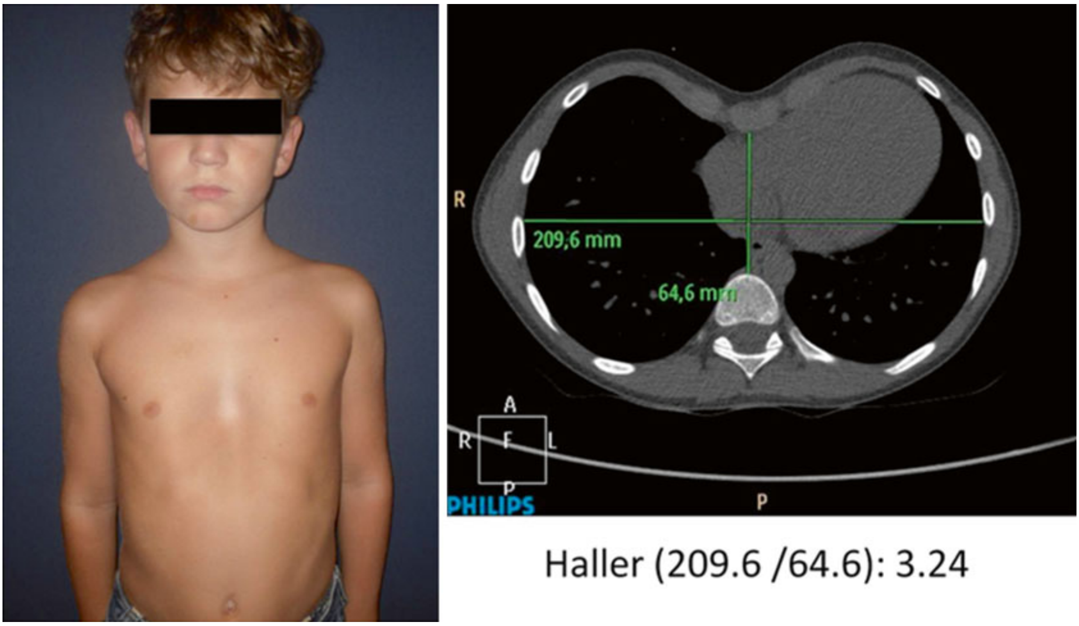


Fig. 7.10 (*Left*) Patient consulting for PE. (*Right*) Chest CT Scan revealing a Haller Index = 3.24. According to the cut-off point of HI, the patient does not have PE

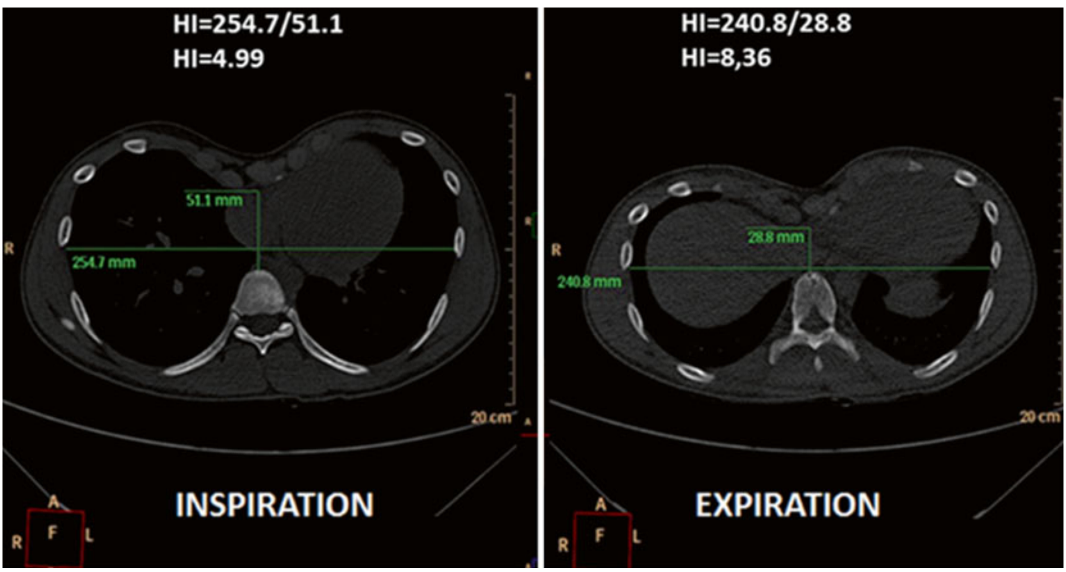


Fig. 7.11 Chest CT Scan of a 16-year-old PE patient. Axial CT images of the same patient are observed at full inspiration and full expiration. Demonstration of measurements performed to assess PE. A significant reduction in the anteroposterior diameter of the chest at full expiration can be noted, while minimal change is observed in the transverse diameter

Authors calculated severity indexes of the deformities from Chest CT scans and from the outline of torso cross sections (i.e., from skin to skin measurements) obtained from optical images. To assess the severity of carinatum defects, the HI-Car (*d*Lat/*d*AP) and a modified pectus index (**moHI-Car**) –

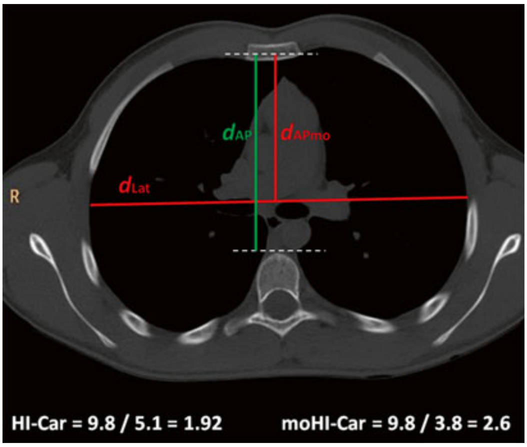


Fig. 7.12 **Haller Index for Pectus Carinatum**: the widest transverse diameter [*dLAT*] is divided by the highest antero-posterior distance [*dAP*]. **Chest CT Haller Index adapted for pectus carinatum**: the widest transverse diameter [*dLAT*] divided by the distance from the central chord to the under surface of the maximal protrusion [*dAPmo*]

which calculates the ratio between the central chord to the under surface of the maximal protrusion (**dAPmo**) by the widest transverse diameter (***d*Lat**) (Fig. 7.12) – were measured. Values of HI-Car ranged from 1.19 to 2.2 (mean = 1.66). Values of Chest CT moHI-Car ranged from 2.27 to 3.1 (mean = 2.5). Regression analyses were performed to compare results from both Chest-CT HI-Car and Chest-CT moHI-Car with results from cross- sections of HI -Car and moHI-car obtained from optical images. Optical measures of cross-sectional deformities correlated well with HI-Car (r^2 = 0.94) and even better with those of moHI-Car (r^2 = 0.96). According to the authors, adaptation of the Haller Index for pectus carinatum deformity evaluation was effective, and consistent with the torso surface deformity measures.

Haller Index for Carinatum = *d*Lat/*d*AP
Modified Haller Index for Carinatum = *d*Lat/*d*APmo

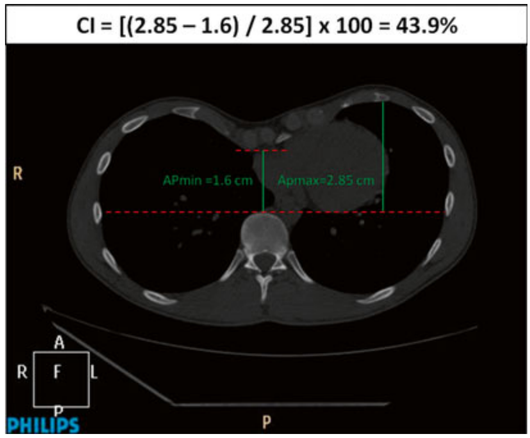


Fig. 7.13 Calculation of the **Correction Index**. In this case it is almost 44 % indicating the patient has a moderate to severe PE

Correction Index

The **C**orrection **I**ndex (**CI**) was described by St. Peter et al. [26] who observed that HI is dependent on width and does not assess the depth of the defect correctly. In their study by utilizing larger cohorts with age-defined groups for controls they concluded that using a height to width ratio of 3.25 as a discriminator to define potential candidates for PE repair could no longer be held true.

Thereby the authors proposed a novel index calculated from chest CT at end-inspiration [26].

A horizontal line is drawn across the anterior spine. Then the CI measures the minimum distance between the posterior sternum and the anterior spine (narrowest point) [AP min], plus the maximum distance between the anterior spine and the anterior portion of the chest (widest point) [AP max]. The difference between those values (widest minus narrowest point), in other words, the amount of defect, is divided by the widest point (Fig. 7.13) and finally multiplied by 100 thus giving the percentage of PE depth the patient is missing. Conversely, it represents the percentage of chest depth to be corrected by bar placement.

Using the CI, a normal distribution is created more clearly for both controls and PE patients with no overlap between them. The gap is in fact large enough to enable a high degree of confidence in defining PE. The key to CI success is that it is blind to chest width and that it defines the distance of the sternum from the goal position.

Correction Index = [(AP max − AP min)/AP max] × 100

The cut-off point of CI is set at 10 % to differentiate controls from PE patients without overlapping. St. Peter et al. [26] statistically demonstrated that a CI > 10 % means that more than 10 % of the chest depth between the anterior chest and the anterior spine is centrally depressed which is by definition PE. With this novel index, the possibility of a high index and no defect or a deep defect with a low index is removed.

Poston et al. [19] validated the findings of St. Peter et al. [26], using the same formula but calculating the CI differently. They recommend a CI of 28 % or greater when correlating statistically with the well known Haller Index cut-off value of 3.25 (which unfortunately has never been validated). These authors also observed that although the HI correlates well with the CI in PE patients with symmetric chest wall deformities, it is quite discrepant in asymmetric cases.

Deformity Indexes

According to Lawson et al. [41] deformity indexes are needed because the HI alone may be inadequate to quantify postoperative changes in the shape of the chest. Individual PE patients may also have chest characteristics that impact the success of repair, many of which would be unlikely to be measured solely by the HI.

They thereby designed a digitizer protocol used by radiologists, which included detailed instructions on how to select the appropriate 5 images to calculate pectus defect severity. Once the measurements were made, the HI and **A**symmetry **I**ndex (AI) were calculated for each slice as T/A and R/L × 100, respectively. A patient's overall HI was defined as the largest of the 5 images calculated. Both radiologists disagreed with the 3.2 threshold used as the cut-off point for eligibility for surgery by insurance companies and numerous surgeons. The AI was defined as the farthest from 100 of the 5 images' calculated value. For this reliability study, the indexes were compared between digitizer measurements and between radiologists for each slice selected. The radiologists had almost perfect agreement on the selection of the slices to be used for the HI and AI. They noted the use of the cross-sectional area is less likely to be impacted by the shape of the chest than any currently used index. The digitizer protocol alleviated potential biases and inconsistencies in data being collected from multiple centers with competing surgical treatments. Although it is more extensive than just determining a single HI or AI as a rough gauge of severity or deformity, it provides a tool for assessing both the need for surgery and the outcome of repair in any future quality monitoring program or to readily study any potential future modifications of the surgical technique (Fig. 7.14) [41].

Asymmetry Index = (R/L) × 100
Interpretation:
When AI = 100; R = L; Symmetric PE
When AI > 100; R > L; Right Asymmetric PE
When AI < 100: R < L; Left Asymmetric PE
This Asymmetry Index is expressed as a percentage ratio

Other surgeons preferred deformity indexes such as the **V**ertebral Index (**VI**) and the **F**ronto **S**agittal **I**ndex (**FSI**) to evaluate the degree of chest wall deformation changes after surgery, using pre- and postoperative radiological examination data.

Kilda et al., for example, concluded that when preparing a PE patient for surgery, it is important

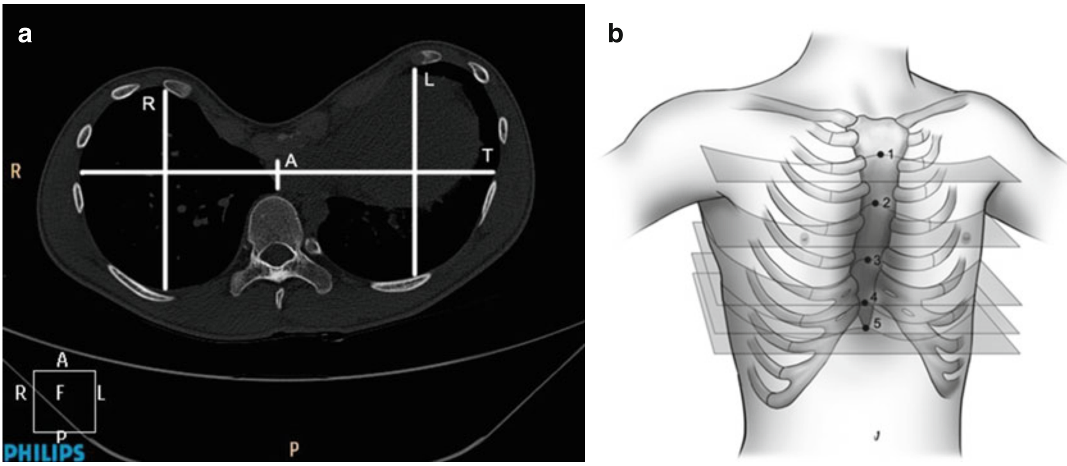


Fig. 7.14 (**a**) Axial CT Scan of a patient with PE. Calculation of the Haller Index and Asymmetry Index. Ref: [*T*] transversal chest dimension; [*R* and *L*] sagittal right and left chest size dimensions; [*A*] sternovertebral distance. (**b**) 5-position protocol for intrathoracic measurement of Haller Index and Asymmetry Index at each cut level. Position 1: the level of the sternomanubrial junction (anterior second rib ends); Position 5: the level of the tip of the xiphoid; Position 4: the level of the end of the body of the sternum; Positions 2 and 3: divide the distance between positions 1 and 4 by 3. Position 2 is one third of the way between positions 1 and 4, and position 3 is two thirds of the way between positions 1 and 4 (calculated by the digitizer technician)

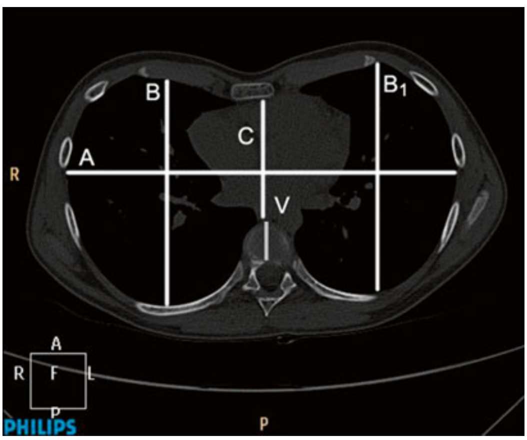


Fig. 7.15 Axial CT scan showing value assessments. [*A*] transversal chest dimension. [*B* and B_1] sagittal right and left chest size dimensions. [*C*] sternovertebral distance. [*V*] vertebral body length

to perform a chest CT scan and give an overall evaluation of the chest shape and deformation degree considering the following cut-off points: VI > 26, FSI < 33 and HI > 3.1 They also concluded the dynamics of deformation is better depicted by means of VI rather than HI (Fig. 7.15) [43, 44].

Vertebral Index = [**V**/(**V** + **C**)] × **100**
Frontosagittal Index = (**C**/**A**) × **100**

Masaoka et al. calculated the steepness index, excavatum volume index and asymmetry index to evaluate the impact of surgical repair on PE patients (Fig. 7.16) [27]. Pre- and postoperative means were estimated for each index but no information about cut-off points was given though.

All measurements improved postoperatively.

Steepness Index = D/W
Excavation Volume Index = O × W/(IA × IB) + (rA × rB)
Asymmetry Index = IA × IB/rA × rB

Lee et al. [28] retrospectively analyzed pre- and postoperative Chest CTs of more than 300 PE patients to obtain new CT indexes: **D**epression

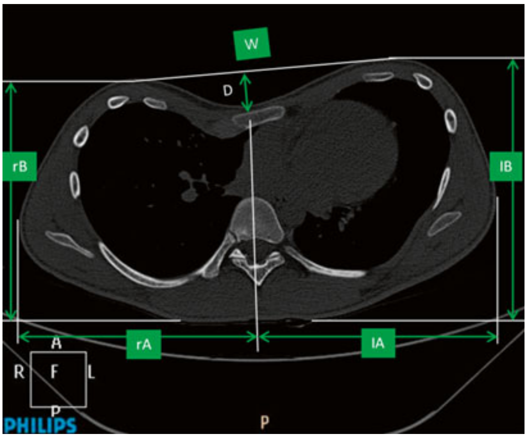


Fig. 7.16 Masaoka et al.'s measurements for deformity indexes *W* distance between the prominent points of the anterior chest wall on both sides, *D* length of the perpendicular line between the center of the anterior table of the sternum and the line showing combination of both prominent points, *rA* length between the right lateral thoracic wall and the vertical line from the center of sternum, *rB* distance between the prominent point of right anterior thoracic wall and the touch line of right back, *IA* length between the left lateral thoracic wall and the vertical line from the center of the sternum, *IB* distance between the prominent point of left anterior thoracic wall and the touch line of left back

Index (**DI**), **A**symmetry **I**ndex (**AI**), **E**ccentricity **I**ndex and **U**nbalance **I**ndex. These were useful in precise understanding of the degrees of depression and asymmetries as well as in comparing morphological changes before and after operative repair of the defect (Fig. 7.17). Evaluation of the AI revealed that treating PE patients with the Nuss technique enabled symmetrical correction of asymmetric PE. Lee et al. postulated that with the modified techniques tailored to each specific type of asymmetry, indications of the Nuss procedure could be expanded essentially to all morphological kinds of PE.

The four thoracic indexes decreased after surgery. When comparing preoperative values of symmetric and asymmetric PE AI values were different (1.036 ± 0.042 vs. 1.107 ± 0.080, $p < 0.01$), but postoperatively the difference became not significant (1.019 ± 0.022 vs. 1.024 ± 0.028, $p = 0.08$), which means asymmetric types are corrected to a symmetric configuration after surgery [28].

Cartoski et al. [6] calculated the HI by T/A, **A**symmetry **I**ndex (AI) by $R/L \times 100$, and Chest

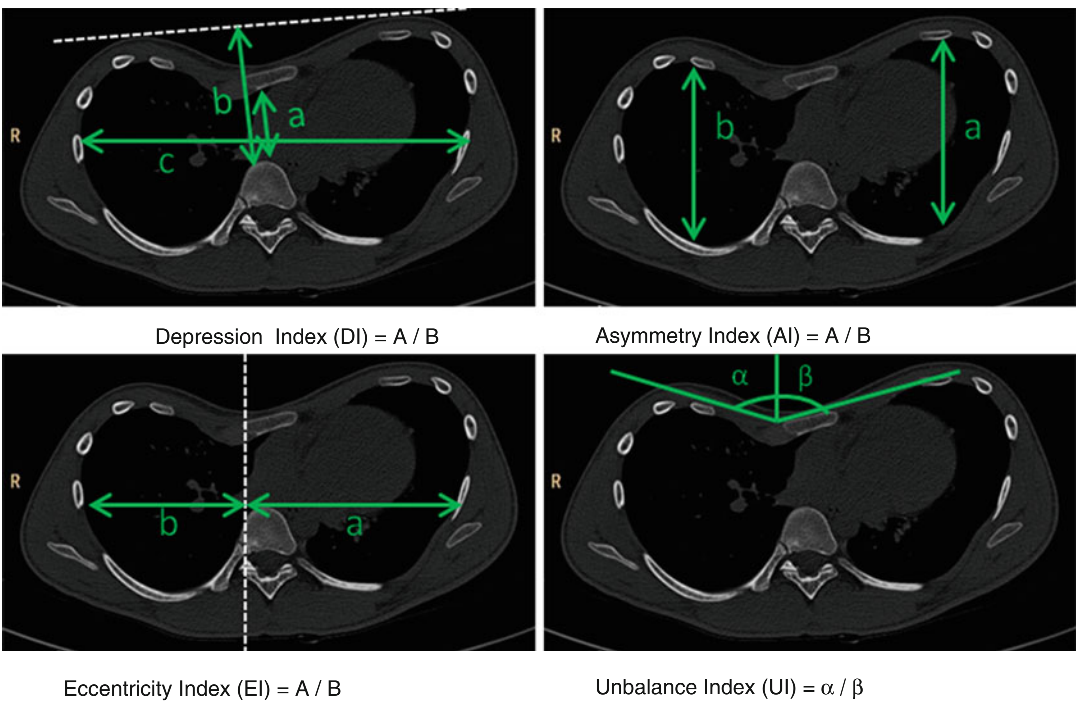


Fig. 7.17 Deformity indexes displaying degrees of Depression, Asymmetry, Eccentricity, and Unbalance

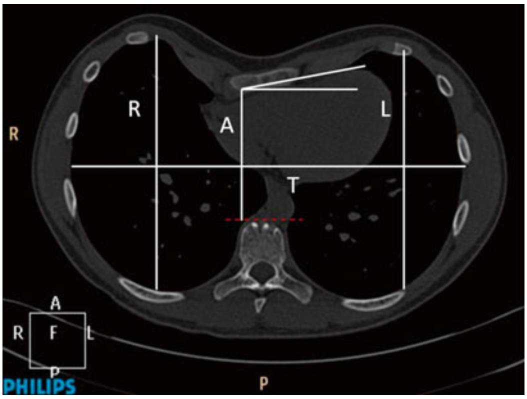


Fig. 7.18 Deformity indexes displaying severity of the Depression, Asymmetry, Chest shape and Torsion angle

Shape Index by T/R. Sternal torsion angle is marked and represents the degree of torsion or tilt to the right (most common) or left (unfrequent). All measurements were measured at maximum distances except for A, which was measured as the minimum distance between the anterior surface of the vertebral column and the deepest portion of the sternum (Fig. 7.18).

Asymmetry Index = R/L × 100
Chest Shape Index = T/R

The authors point out that a long PE has surgical relevance relating to choices made during the corrective procedure. The Nuss procedure may require 2 bars instead of 1 if the patient has a depression affecting the chest that the addition of only 1 bar fails to correct the condition entirely. Two bars are not always necessary for a long depression as some patients, especially younger children, have greater flexibility in their thoracic cavity and experience a good correction with a single bar.

Chest CT scans allow greater perception of asymmetry inside the thoracic cavity in comparison with the external clinical perception. Although no cut-off point for surgical eligibility has been set for the AI, this index is a likely predictor of surgical outcome. Since it is a ratio of two sides of the PE depression values away from 100 are merely a reflection of whether the right or the left side of the depression is deeper.

Sternal torsion measured at an angle >30° is considered severe, whereas mild torsion is applied to any angle <30°. Sternal torsion to the right often appears with asymmetry to the right and the other way around in general. A sternal torsion to the left changes the surgical strategy to avoid injuring the heart. A severely twisted sternum upon correction does not always completely flatten and can leave a slight protuberance in the appearance of the chest.

Kim et al. [29] believe conventional indexes that define the severity of PE have several limitations, e.g. they are manually calculated and cannot supply information about asymmetry. The authors developed four automatized indexes that can represent both the depression and the asymmetry of the chest-wall by CT Scan. Three indexes, including **E**ccentricity **I**ndex (EI), **F**latness **I**ndex (FI), and **C**ircularity **I**ndex (**CI**), were suggested to represent the depression of the chest-wall, and one index, **R**otation **I**ndex (**RI**), to represent the asymmetry of the chest-wall. The suggested indexes showed clear trends of change with the severity of chest-wall deformation in regards to both the depression and the asymmetry. Results of statistical analysis showed high correlation between the new indexes and HI, showing possibility of replacing HI.

Cardiac Compression and Cardiac Asymmetry Index

According to Kim et al. [31], the chest CT findings of PE include displacement of the heart into the left hemithorax with mild clockwise rotation and a pancake-like appearance of the heart with an increase of the frontal silhouette to the left. The possible mechanisms that produce circulatory problems include: (1) decreased inflow due to cardiac rotation and twisting of the great veins; (2) cardiac compression; (3) impaired diastolic expansion; and (4) decreased respiratory effort. The **C**ardiac **C**ompression **I**ndex (**CCI**) derives from the H/M ratio and the **C**ardiac **A**symmetry **I**ndex (**CAI**) derives from the P/M ratio (Fig. 7.19).

Modified Cardiac Compression Index

Albertal et al. [24] calculated the cardiac compression index (CCI) from chest CT by dividing the cardiac transverse diameter by the cardiac antero-posterior diameter. CCI increased significantly during end-expiration, primarily driven by an increase on the cardiac transverse diameter.

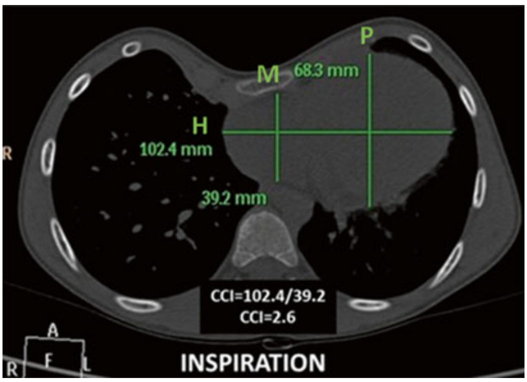


Fig. 7.19 Calculation of the Cardiac Compression Index (*CCI*) and the Cardiac Asymmetry Index (CAI) from a Chest CT at end-inspiration. CCI = 102.4/39.2 = 2.6 (Cut-off point: 1.82); CAI = 68.3/39.2 = 1.74 (Cut-off point 1.15)

Surgical indication was found in 71 % and 91 % (20 % difference) of patients during end-inspiration and end-expiration, respectively ($p<0.05$) (Fig. 7.20). Authors therefore recommend performing the CT at end-expiration.

MRI Indexes

These include all the aforementioned indexes and cardiac indexes for delineating the anatomical and physiological components of PE as well as measuring the results of treatment [32]. As already said, the diagnoses of PE is clinical. Nonetheless the quantitative measurement of the deformity has been evaluated by means of radiographies and CTs. Recent reports in the literature have recognized the problem of radiation and some authors commenced using MRI to diagnose and assess the severity of the pectus deformity [33–35]. Future directions could eventually include the routine acquisition of inspiratory and expiratory MRI sequences. Research has shown that this may provide more physiological information; in expiration, the deformity may worsen [36]. Furthermore, cine MRI has demonstrated to be capable of evaluating both chest morphology and chest wall kinetics, and may well add important diagnostic information [45].

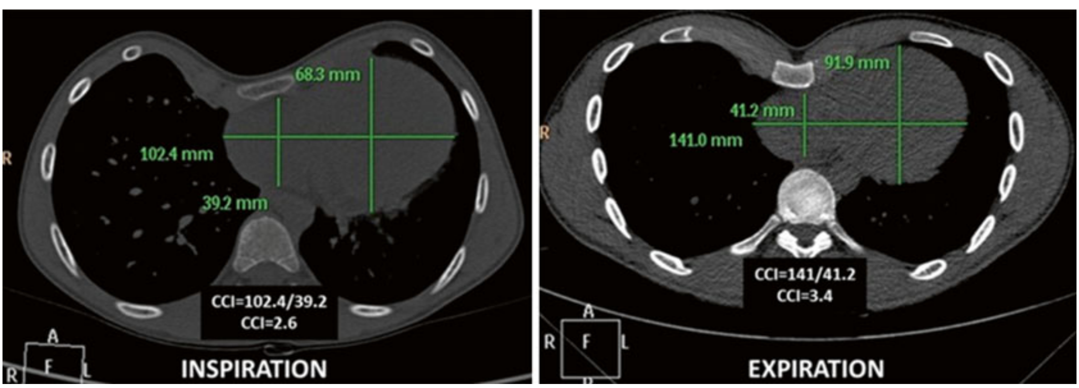


Fig. 7.20 Axial images of the heart at full inspiration and full expiration. Measurements performed to assess cardiac compression are shown. There is a significant increase in the cardiac transverse diameter at full expiration and no valuable modifications in the cardiac anteroposterior diameter. Notice the maximal cardiac anteroposterior diameter revealed a sizeable increase of 5.1 % at full expiration whereas the maximal cardiac transverse diameter, 37.7 %

Survey

Because of the large number of thoracic indexes reported worldwide and the diverse variety of diagnostic tools available today, there is no consensus on which is the best thoracic index to diagnose, assess severity, define strategies within treatment, and quantify postoperative thoracic shape changes. For this reason, a selected group of international chest wall malformations experts were consulted by means of a web-based survey. The main objective was to start classifying thoracic indexes and to establish a unifying criterion. The entire project was designed, implemented and analyzed by Drs. Martinez-Ferro and Park, and supervised by the Chest Wall International Group (CWIG) president, Dr. H. Pilegaard. The web-based survey was performed using the Survey Monkey™ (Palo Alto, CA, USA) website. It consisted of 10 multiple choice questions about the preoperative and intraoperative management of PE patients, focusing on the current use of the most commonly used thoracic indexes for surgical planning. In general, more than one answer could be selected per question. The survey was confidential and anonymous (Table 7.3).

Table 7.3 Ten multiple-choice questionnaire. Web-based survey

(Q1) Which preoperative studies do you use <u>in ALL (100 %) your patients</u> with pectus excavatum?
Chest X-ray
Chest CT
3D Chest CT
MRI
Cardiac MRI
Cardiac US
Echo stress
Cardiopulmonary test
Exercise stress test
24-h Holter monitoring
Pulmonary function test
Plethismography
Thoracic spine X-ray
Nickel allergy test and/or other metal allergy tests
Other (describe)
(Q2) In your opinion, thoracic indexes for treatment decision-making are?
Essential
Very useful
Barely needed
Useless
(Q3) If a, b or c, why do you use them?
Because Insurance Companies/Health System request them
Because they help you to identify the severity of the deformity
Because they may change the surgical technique and/or approach
Because they help you describe the problem to the patient
I don't use them at all
(Q4) Which Indexes do you routinely use in your practice?
Haller Index
Modified Haller Index
Correction Index
Welch Index (X-ray)
Asymmetry Index
Cross-sectional chest area
Depression Index
Eccentricity Index
Flatness Index
Circularity Index
Unbalance Index
CT-derived Cardiac Compression Index
CT-derived Correction Index (Kansas)
Anthropometric Index
Vertebral Index
Frontosagittal Index
Other (describe)
(Q5) The Haller Index is:
Essential
Very useful
Useful
Useless
(Q6) In your opinion, a 3.25 Haller index as cut-off value between surgical and non-surgical patients is:
Correct
Incorrect
(Q7) You order a Haller Index
In inspiration
In expiration
I do not specify it in my order

Table 7.3 (continued)

(Q8) If you had to choose only one Index to use, which one would you prefer?
Haller Index
Modified Haller Index
Correction Index
Welch Index (X-ray)
Asymmetry Index
Cross-sectional chest area
Depression Index
Eccentricity Index
Flatness Index
Circularity Index
Unbalance Index
CT-derived Cardiac Compression Index
CT-derived Correction Index (Kansas)
Anthropometric Index
Vertebral Index
Frontosagittal Index
Other (describe)
(Q9) Which is your preferred technique for the correction of pectus excavatum?
Resective surgery (Ravitch and modifications)
Nuss Technique (and modifications)
Bardaji Ventura Technique
Other (specify)
(Q10) If you selected the "Nuss Technique", would you consider important to have a way of predicting in advance how many bars will the patient need?
Yes
No

The invitation, together with 3 reminders, were sent to chest wall malformation experts between March and April 2014. After the 2 months prospective data collection period, responses were downloaded to a Microsoft Excel™ file (Redmond, WA, USA) for descriptive analyses of answers. Duplicate responses corresponding to the same author were removed by deleting the less complete response.

Results

Of the 334 surveyed chest wall malformation experts, 92 answered the questions and a mean of 86, range: 92–74 (25.74 %) participated in the project. Sixty-one percent were males.

In accordance with **Question 1** (**Q1**), for preoperative evaluation, 58.7 % of responders tend to indicate a Chest CT Scan whereas 50.2 %, order a Chest X-Ray and/or an Echocardiography. A 3D Chest CT Scan is opted by 22.8 % of the PE experts, and a Thoracic Spine – X – Ray, by only 7.6 % of them. Nobody will indicate a cardiac MRI or a Plethismography. Moreover, while 50 % of the surgeons always request a pulmonary function test, those exams involving exercise (as treadmill exercise, stress-echo US or cardiopulmonar tests) are seemingly to be ordered by only a 12 % (Fig. 7.21).

Question 2 (**Q2**) is about the value of thoracic indexes for treatment decision-making, 14.3 % of chest wall malformation experts reported they are essential; 45 %, very useful; 35.1 % barely needed and 5.6 % useless (Fig. 7.22).

The reason for using thoracic indexes is detailed in the answers to **Question 3** (**Q3**).

Forty-four of those who do not consider thoracic indexes useless (72.1 %), employ them because they help to better identify the severity of the deformity and 30 (49.2 %), because thoracic indexes help to describe the problem to the patient. Insurance Companies/Health Systems are a less significant reason, and only 13.51 % of the surgeons will use thoracic indexes to change their surgical technique and/or approach (Fig. 7.23).

According to **Question 4** (**Q4**), 89.78 % of responders prefer to employ in their routine practice either the Haller Index (79.55 %) or a modified Haller Index (10.23 %) (Fig. 7.24).

In **Question 5** (**Q5**) 86.36 % of the surgeons consider the Haller Index: Essential, Useful and Very Useful (Fig. 7.25).

Surprisingly more than half of the experts (56.32 %) consider a cut-off value of 3.25 incorrect, **Question 6** (**Q6**), (Fig. 7.26). This seems to be a contradiction when considering that the analysis of Q4 and Q5 reveal that almost 90 % responders indicate a Haller Index routinely, and 86.36 % believe it is essential, useful and very useful.

Results of Q6 are also in conflict with those revealed in **Question** 8 (**Q8**), as almost 70 % of responders state that they prefer the Haller Index

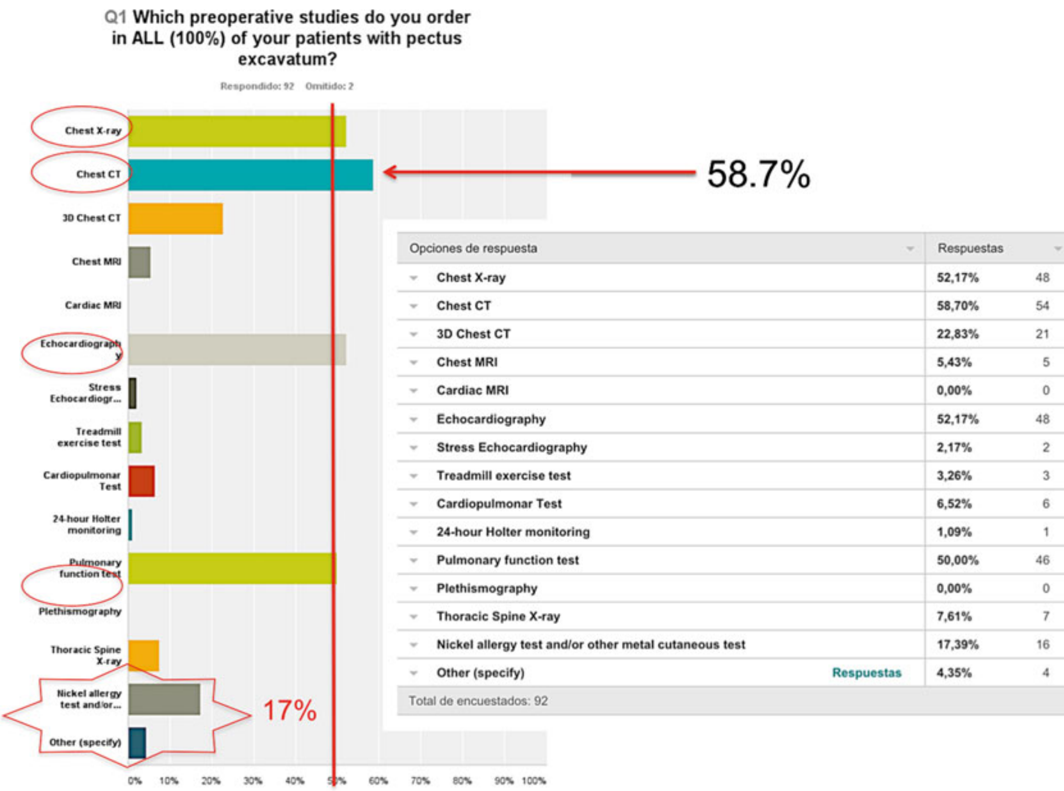
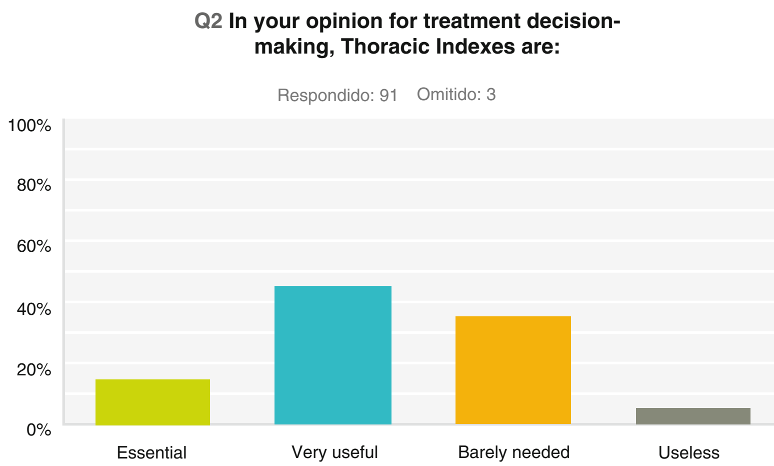


Fig. 7.21 Question 1 results

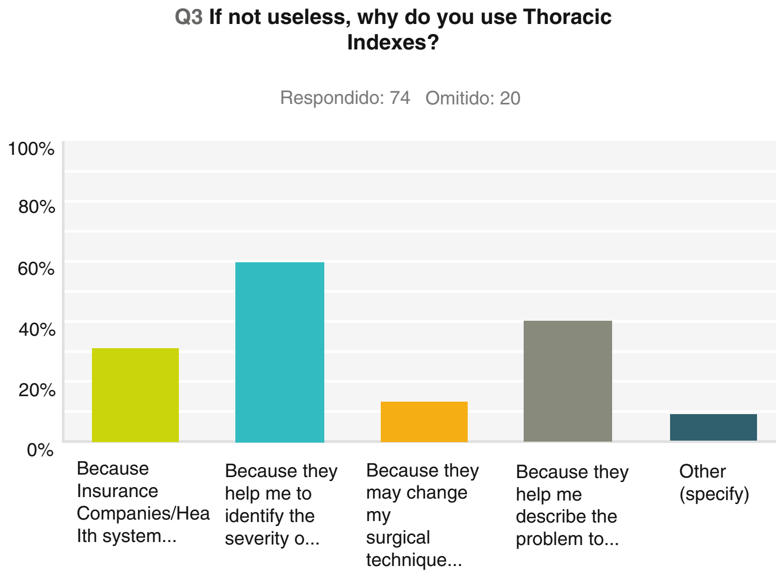
Fig. 7.22 Question 2 results

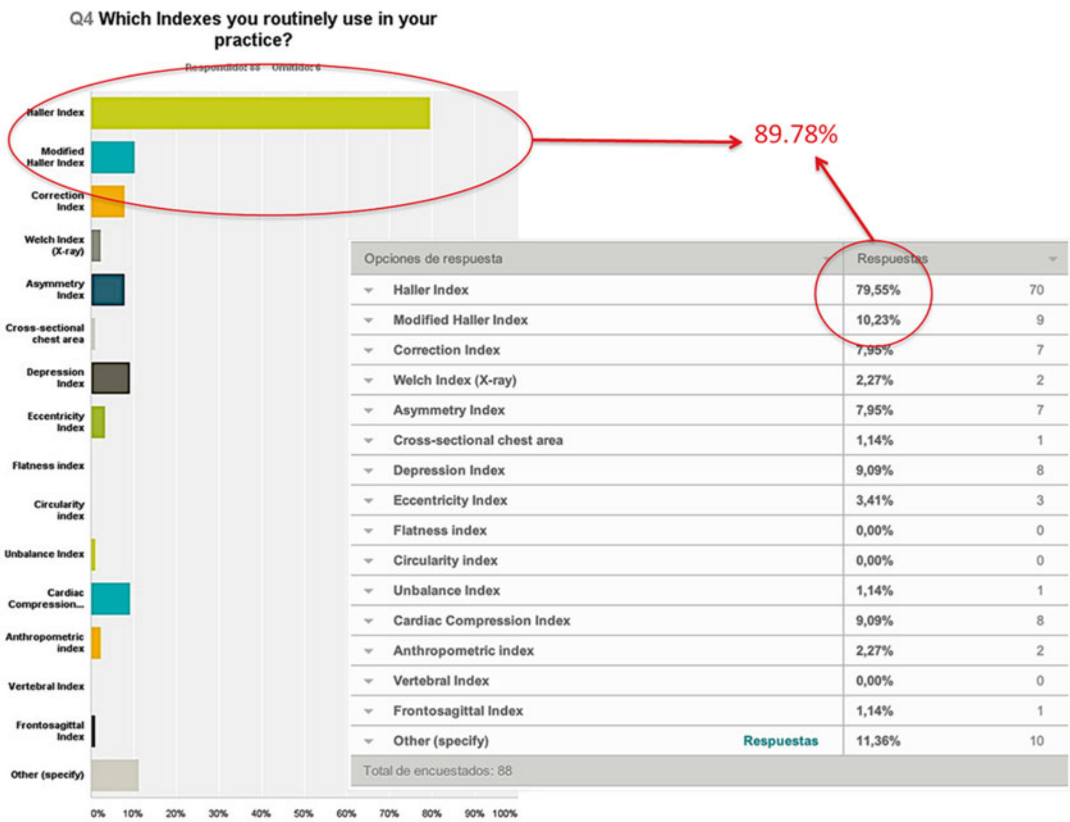


or a modified Haller Index if they had to choose only one single index (Fig. 7.27).

When asking if the Haller Index should be ordered in Inspiration or Expiration in **Q**uestion **7** (**Q7**), 65.48 % reported it is irrelevant, whereas 19.05 % and 15.48 % said they request it during expiration and inspiration, respectively (Fig. 7.28).

Fig. 7.23 Question 3 results





Opciones de respuesta	Respuestas	
Haller Index	79,55%	70
Modified Haller Index	10,23%	9
Correction Index	7,95%	7
Welch Index (X-ray)	2,27%	2
Asymmetry Index	7,95%	7
Cross-sectional chest area	1,14%	1
Depression Index	9,09%	8
Eccentricity Index	3,41%	3
Flatness index	0,00%	0
Circularity index	0,00%	0
Unbalance Index	1,14%	1
Cardiac Compression Index	9,09%	8
Anthropometric index	2,27%	2
Vertebral Index	0,00%	0
Frontosagittal Index	1,14%	1
Other (specify) Respuestas	11,36%	10
Total de encuestados: 88		

Fig. 7.24 Question 4 results

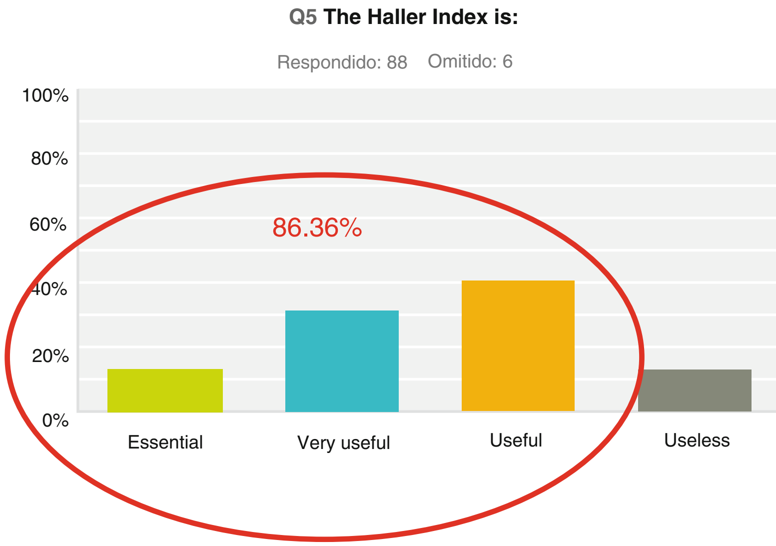


Fig. 7.25 Question 5 results

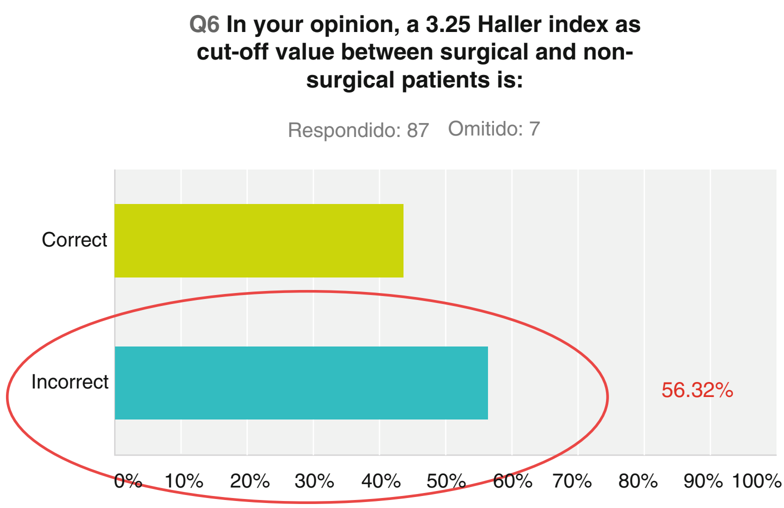


Fig. 7.26 Question 6 results

Question 9 (**Q9**) is about the preferred surgical technique for the correction of PE. Most surgeons (89.53 %) advocate PE repair with the Nuss technique, whereas a few use the Ravitch procedure (3.49 %) or its variants, or the Bardaji – Ventura technique (1.16 %) (Fig. 7.29).

For those chest wall malformation experts who selected the Nuss technique in Question 9, 75.9 % consider important to have an index that may help to predict in advance the need for 1 or 2 bars. **Question 10** (**Q10**) (Fig. 7.30).

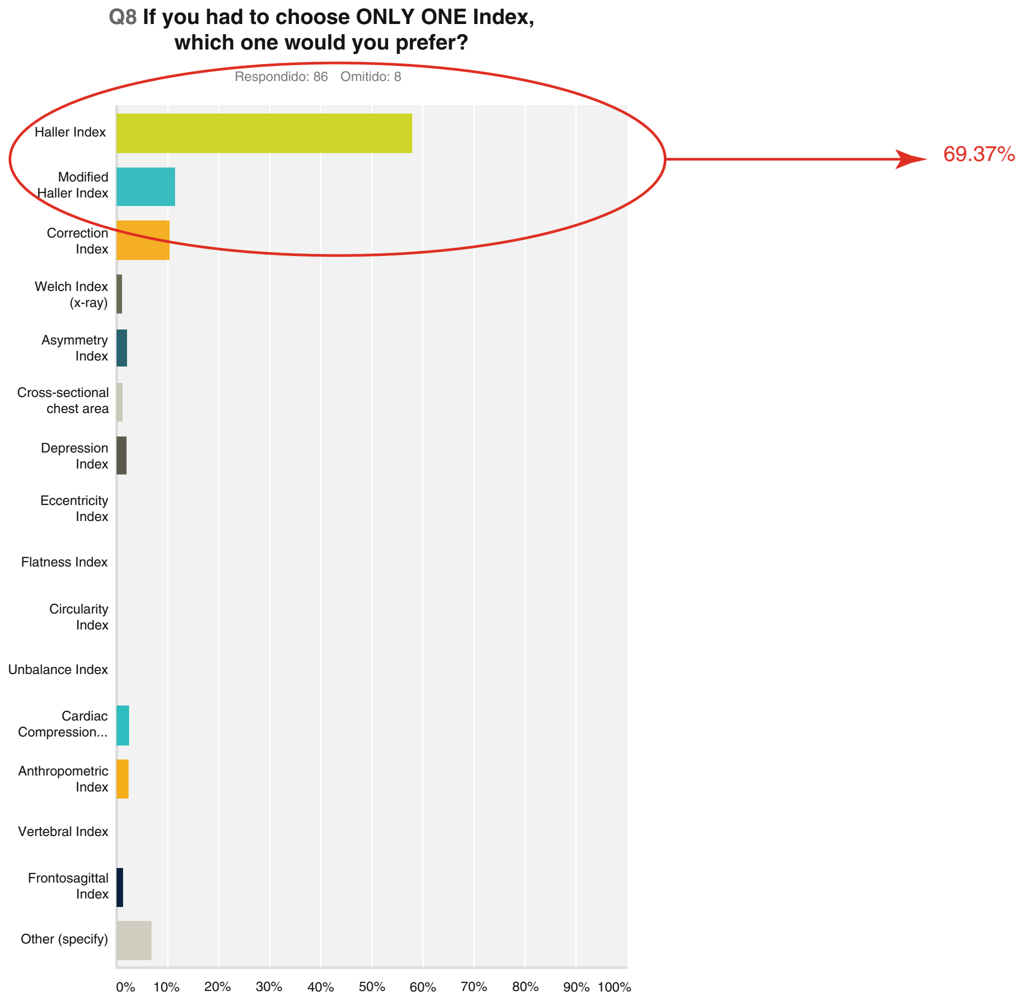


Fig. 7.27 Question 8 results

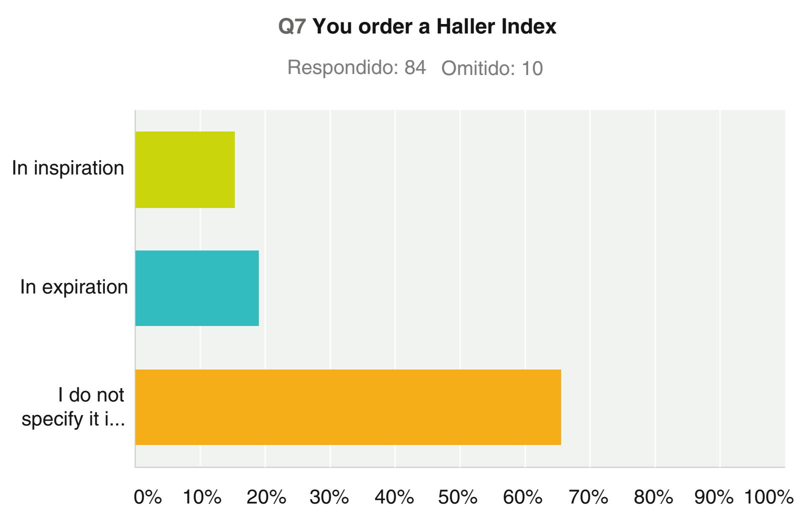


Fig. 7.28 Question 7 results

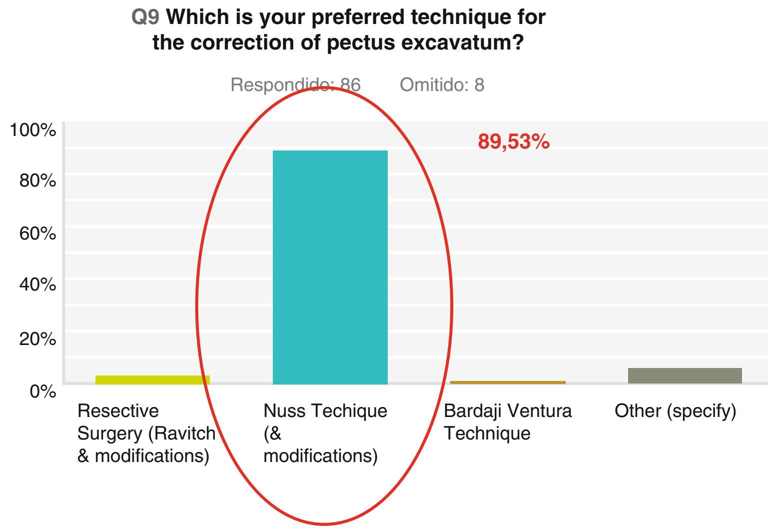


Fig. 7.29 Question 9 results

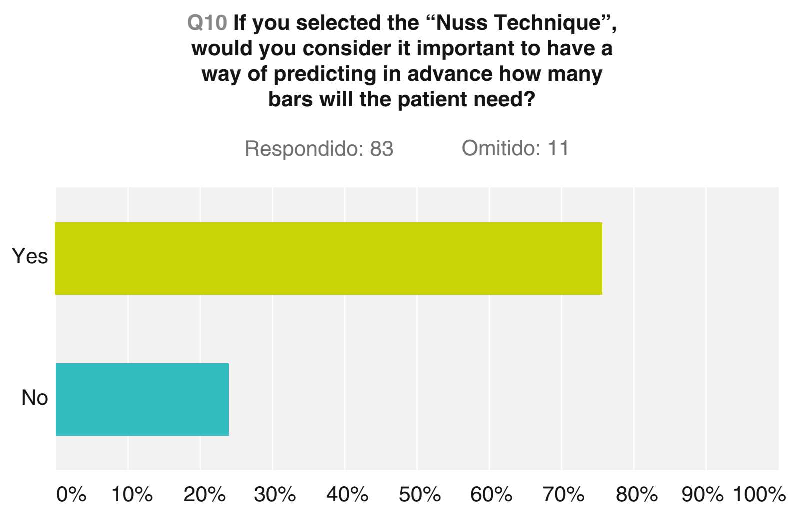


Fig. 7.30 Question 10 results

Conclusions

The survey revealed the need to:

- establish an order and propose a classification for the large variety of thoracic indexes in existence,
- replace the Haller Index and find a new gold standard,
- validate all indexes before putting them into practice

After analyzing them one by one in this chapter, it has to be concluded that there is currently no thoracic index without limitations. Perhaps the perfect index will be a mathematical combination of several different indexes. Perhaps it will be a single index still to be discovered. In any case, the index must be a diagnostic and assessment tool that will enable to:

1. Establish the difference between PE patients and controls without overlapping.
2. Evaluate the severity of the deformity without biases.
3. Quantify the cardiopulmonary impact of the deformity without biases
4. Help to define therapeutical strategies
5. Quantify improvements after surgical repair or after non-operative treatment.

Most probably this effort could only be achieved by an international “task-force” composed by experts working in centers with vast experience in treating thoracic wall deformities. In this case, there is room for a society such as the Chest Wall International Group that gather many of such experts and centers. It may take many years to find a universal, validated thoracic index, but the labor will be worthwhile.

References

1. Haje SA, Haje Dde P, Silva Neto M, e Cassia Gde S, Batista RC, de Oliveira GR, Mundim TL. Pectus deformities: tomographic analysis and clinical correlation. Skeletal Radiol. 2010;39(8):773–82.
2. Haje SA, Harcke HT, Bowen JR. Growth disturbance of the sternum and pectus deformities: imaging studies and clinical correlation. Pediatr Radiol. 1999;29(5):334–41.
3. Haje SA, Haje Dde P. Abordagem ortopédica das deformidades pectus: 32 anos de estudos. Rev Bras Ortop. 2009;44(3):191–8.
4. Daunt SW, Cohen JH, Miller SF. Age-related normal ranges for the Haller index in children. Pediatr Radiol. 2004;34(4):326–30.
5. Rebeis EB, Campos JR, Moreira LF, Pastorino AC, Pêgo-Fernandes PM, Jatene FB. Variation of the Anthropometric Index for pectus excavatum relative to age, race, and sex. Clinics (Sao Paulo). 2013; 68(9):1215–9.
6. Cartoski MJ, Nuss D, Goretsky MJ, Proud VK, Croitoru DP, Gustin T, Mitchell K, Vasser E, Kelly Jr RE. Classification of the dysmorphology of pectus excavatum. J Pediatr Surg. 2006;41(9):1573–81.
7. Derveaux L, Clarysse I, Ivanoff I, Demedts M. Preoperative and postoperative abnormalities in chest x-ray indices and in lung function in pectus deformities. Chest. 1989;95(4):850–6.
8. Malek MH, Berger DE, Housh TJ, Marelich WD, Coburn JW, Beck TW. Cardiovascular function following surgical repair of pectus excavatum: a meta-analysis. Chest. 2006;130(2):506–16. Review.
9. Maagaard M, Tang M, Ringgaard S, Nielsen HH, Frøkiær J, Haubuf M, Pilegaard HK, Hjortdal VE. Normalized cardiopulmonary exercise function in patients with pectus excavatum three years after operation. Ann Thorac Surg. 2013;96(1):272–8.
10. Rebeis EB, Campos JR, Fernandez A, Moreira LF, Jatene FB. Anthropometric index for pectus excavatum. Clinics (Sao Paulo). 2007;62(5):599–606.
11. Knutson U. Measurement of thoracic deformities. A new technique giving objective and reproducible results. Scand J Thorac Cardiovasc Surg. 1967; 1(1):76–9.
12. Horst M, Albrecht D, Drerup B. Objective determination of the shape of the anterior chest wall using moiré topography. Method and development of dimension-free indices for the evaluation of funnel chest. Z Orthop Ihre Grenzgeb. 1985;123(3):357–64. German.
13. Backer OG, Brunner S, Larsen V. The surgical treatment of funnel chest. Initial and follow-up results. Acta Chir Scand. 1961;121:253–61.
14. Backer OG, Brunner S, Larsen V. Radiologic evaluation of funnel chest. Acta Radiol. 1961;55:249–56.
15. Hümmer HP, Willital GH. Morphologic findings of chest deformities in children corresponding to the Willital-Hümmer classification. J Pediatr Surg. 1984;19(5):562–6.
16. Ohno K, Nakahira M, Takeuchi S, Shiokawa C, Moriuchi T, Harumoto K, Nakaoka T, Ueda M, Yoshida T, Tsujimoto K, Kinoshita H. Indications for surgical treatment of funnel chest by chest radiograph. Pediatr Surg Int. 2001;17(8):591–5.
17. Welch KJ. Satisfactory surgical correction of pectus excavatum deformity in childhood; a limited opportunity. J Thorac Surg. 1958;36(5):697–713.
18. Shamberger RC, Welch KJ. Surgical repair of pectus excavatum. J Pediatr Surg. 1988;23(7):615–22.
19. Poston PM, Patel SS, Rajput M, Rossi NO, Davis JE, Turek JW. Defining the role of chest radiography in determining candidacy for pectus excavatum repair. Innovations (Phila). 2014;9(2):117–21; discussion 121.
20. Khanna G, Jaju A, Don S, Keys T, Hildebolt CF. Comparison of Haller index values calculated with chest radiographs versus CT for pectus excavatum evaluation. Pediatr Radiol. 2010;40(11):1763–7.
21. Mueller C, Saint-Vil D, Bouchard S. Chest x-ray as a primary modality for preoperative imaging of pectus excavatum. J Pediatr Surg. 2008;43(1):71–3.
22. Haller Jr JA, Kramer SS, Lietman SA. Use of CT scans in selection of patients for pectus excavatum surgery: a preliminary report. J Pediatr Surg. 1987; 22(10):904–6.
23. Haller Jr JA, Scherer LR, Turner CS, Colombani PM. Evolving management of pectus excavatum based on a single institutional experience of 664 patients. Ann Surg. 1989;209(5):578–82; discussion 582–3.
24. Albertal M, Vallejos J, Bellia G, Millan C, Rabinovich F, Buela E, Bignon H, Martinez-Ferro M. Changes in chest compression indexes with breathing underestimate surgical candidacy in patients with pectus excavatum: a computed tomography pilot study. J Pediatr Surg. 2013;48(10):2011–6.
25. Birkemeier KL, Podberesky DJ, Salisbury S, Serai S. Breathe in… breathe out… stop breathing: does phase of respiration affect the Haller index in patients with pectus excavatum? AJR Am J Roentgenol. 2011;197(5):W934–9.
26. St Peter SD, Juang D, Garey CL, Laituri CA, Ostlie DJ, Sharp RJ, Snyder CL. A novel measure for pectus excavatum: the correction index. J Pediatr Surg. 2011;46(12):2270–3.

27. Masaoka A, Kondo S, Sasaki S, Hara F, Mizuno T, Yamakawa Y, Kobayashi T, Fujii Y. Thirty years' experience of open-repair surgery for pectus excavatum: development of a metal-free procedure. Eur J Cardiothorac Surg. 2012;41(2):329–34.
28. Lee C, Park HJ, Lee S. New computerized tomogram (Ct) indices for pectus excavatum: tools for assessing modified techniques for asymmetry in Nuss repair. Chest. 2004;126(4_MeetingAbstracts):777S-a-777S.
29. Kim HC, Park HJ, Ham SY, Nam KW, Choi SY, Oh JS, Choi H, Jeong GS, Park SW, Kim MG, Sun K. Development of automatized new indices for radiological assessment of chest-wall deformity and its quantitative evaluation. Med Biol Eng Comput. 2008;46(8):815–23.
30. Chu ZG, Yu JQ, Yang ZG, Peng LQ, Bai HL, Li XM. Correlation between sternal depression and cardiac rotation in pectus excavatum: evaluation with helical CT. AJR Am J Roentgenol. 2010; 195(1):W76–80.
31. Kim M, Lee KY, Park HJ, Kim HY, Kang EY, Oh YW, Seo BK, Je BK, Choi EJ. Development of new cardiac deformity indexes for pectus excavatum on computed tomography: feasibility for pre- and post-operative evaluation. Yonsei Med J. 2009;50(3):385–90.
32. Humphries CM, Anderson JL, Flores JH, Doty JR. Cardiac magnetic resonance imaging for perioperative evaluation of sternal eversion for pectus excavatum. Eur J Cardiothorac Surg. 2013;43(6):1110–3.
33. Marcovici PA, LoSasso BE, Kruk P, Dwek JR. MRI for the evaluation of pectus excavatum. Pediatr Radiol. 2011;41(6):757–8.
34. Lo Piccolo R, Bongini U, Basile M, Savelli S, Morelli C, Cerra C, Spinelli C, Messineo A. Chest fast MRI: an imaging alternative on pre-operative evaluation of pectus excavatum. J Pediatr Surg. 2012;47(3):485–9.
35. Birkemeier KL, Podberesky DJ, Salisbury S, Serai S. Limited, fast magnetic resonance imaging as an alternative for preoperative evaluation of pectus excavatum: a feasibility study. J Thorac Imaging. 2012;27(6):393–7.
36. Raichura N, Entwisle J, Leverment J, Beardsmore CS. Breath-hold MRI in evaluating patients with pectus excavatum. Br J Radiol. 2001;74(884):701–8.
37. Binazzi B, Innocenti Bruni G, Gigliotti F, Coli C, Romagnoli I, Messineo A, Lo Piccolo R, Scano G. Effects of the Nuss procedure on chest wall kinematics in adolescents with pectus excavatum. Respir Physiol Neurobiol. 2012;183(2):122–7.
38. Gürkan U, Aydemir B, Aksoy S, Akgöz H, Tosu AR, Öz D, Güngör B, Yılmaz H, Bolca O. Echocardiographic assessment of right ventricular function before and after surgery in patients with pectus excavatum and right ventricular compression. Thorac Cardiovasc Surg. 2014;62(3):231–5.
39. Rodrigues PL, Direito-Santos B, Moreira AH, Fonseca JC, Pinho AC, Rodrigues NF, Henriques-Coelho T, Correia-Pinto J, Vilaça JL. Variations of the soft tissue thicknesses external to the ribs in pectus excavatum patients. J Pediatr Surg. 2013;48(9):1878–86.
40. Poncet P, Kravarusic D, Richart T, Evison R, Ronsky JL, Alassiri A, Sigalet D. Clinical impact of optical imaging with 3-D reconstruction of torso topography in common anterior chest wall anomalies. J Pediatr Surg. 2007;42(5):898–903.
41. Lawson ML, Barnes-Eley M, Burke BL, Mitchell K, Katz ME, Dory CL, Miller SF, Nuss D, Croitoru DP, Goretsky MJ, Kelly Jr RE. Reliability of a standardized protocol to calculate cross-sectional chest area and severity indices to evaluate pectus excavatum. J Pediatr Surg. 2006;41(7):1219–25.
42. Nakahara K, Ohno K, Miyoshi S, Maeda H, Monden Y, Kawashima Y. An evaluation of operative outcome in patients with funnel chest diagnosed by means of the computed tomogram. J Thorac Cardiovasc Surg. 1987;93(4):577–82.
43. Kilda A, Basevicius A, Barauskas V, Lukosevicius S, Ragaisis D. Radiological assessment of children with pectus excavatum. Indian J Pediatr. 2007;74(2): 143–7.
44. Kilda A, Lukosevicius S, Barauskas V, Jankauskaite Z, Basevicius A. Radiological changes after Nuss operation for pectus excavatum. Medicina (Kaunas). 2009;45(9):699–705.
45. Herrmann KA, Zech C, Strauss T, Hatz R, Schoenberg S, Reiser M. Cine MRI of the thorax in patients with pectus excavatum. Radiologe. 2006;46(4):309–16. German.