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Evolution of the Nuss procedure for the repair of Pectus Excavatum: Our expereience

Thesis of specialization

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CONTENTS

Acknowledgments

La personale curiosità verso la tecnica di correzione del **P**ECTUS **E**XCAVATUM , nata per l'involontaria partecipazione ad una sessione dedicata di congresso di chirurgia toracica e accresciuta con la ricercata partecipazione a convegni tematici, ma soprattutto dalla disponibilità del mio Professore (1) ad accondiscendere alla mia aspirazione di completare il percorso di specializzazione con un periodo di training sulla tematica e l'altrettanto disponibilità del Prof. Antonio Messineo (2) ad accogliermi nel Suo Reparto di chirurgia pediatrica dell'Ospedale Mayer di Firenze dove ha realizzato il Centro P.E. , mi consentono l'orgoglio di terminare il corso di studi proprio con questa tesi.

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Una citazione la merita l'Equipe, sia per la composizione specialistica di chirurgia pediatrica e chirurgia plastica, sia per l'eccezionale dote umana che contraddistingue i suoi componenti e la certosina capacità di scelta del suo Capo, il quale la arricchisce, nei vari momenti, con specializzazioni e conoscenze tecniche di altri sanitari.

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Introduction

Pectus **E**xcavatum represents a depression in the anterior chest wall as a result of dorsal deviation of the sternum and the third-seventh rib or costal cartilage.

Epidemiology

Pectus deformities are the most common congenital chest wall deformities. PE is the most common among all chest wall deformities representing 90% of all cases and occures in 8 of 1,000 live births. More specifically, the human incidence of pectus excavatum varies from 38 per 10.000 births among white infants, to 7 per 10.000 births among black infants, to 20 per 10.000 infants categorized as other than black or white, in a 1975 Collaborative Perinatal Project in the United States . Males are more often affected, with a gender distribution between 2:1 and 9:1. Even if PE occurs sporadically, a genetic predisposition seems likely, since a positive family history could be found in up to 43% of PE cases. However, a specific genetic defect has not yet been found. Most cases of PE could be noted clinically within the first year of life, but primary occurrence in puberty has been also described. Mostly, chest wall deformities represent a single anomaly, but they could also be one manifestation of various genetic disorders. In this context, Kotzot and Schwabegger [55] gave a comprehensive overview about all syndromes associated with chest wall deformities: Cardiofaciocutaneous syndrome, Holt-Oram syndrome, Homocystinuria, Marfan syndrome **(Fig. 1),** Noonan syndrome, Osteogenesis imperfecta type I, III, IV, are the most important.

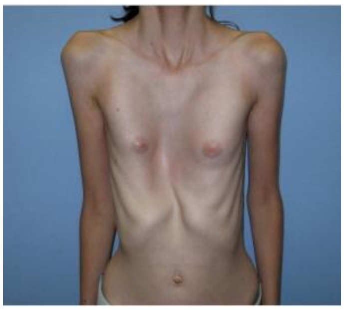


FIGURE 1. Pectus Excavatum in Marfan syndrome

History of PE description

Recognition of the condition in antiquity is not reported, but as it is a visible, inherited abnormality, surely this represents inadequate searching or reporting. The earliest reported cases now appear to come from a report of 176 excavated graves in Hungary. Two PE sternums were found of 48 evaluable breast bones graves dated from the 10th to the 16th centuries. Published photographs clearly show the sternal depression [39] (**Fig 2)**.

Recently, excavations below Ripon Cathedral in Yorkshire, England identified a very well-preserved skeleton, radiocarbon dated to the late 15th century AD, showing features of pectus carinatum. The burial was that of a young adult female, and the position of the grave suggested that she was of high social status.

FIGURE 2 Pectus excavatum, grave 57, lateral view.

In 1594 Schenck published a case of PE identified by Bauhinus. This is the earliest case report that has been cited. Numerous case reports appeared in the 19th century: A documented description of an appearance of the thorax could be found in 1860 by Woillez. In 1863, Von Luschka reported on a 6cm deep depression in the thorax of a 24 year old man. In 1870, Eggel published the first comprehensive case report of a patient with a funnel formed thorax depression calling it a “Miraculum Naturae”. Individual case reports followed; by Williams in 1872, Fleschi in 1873 and Hagmann in 1888. A notable report of five patients came from Ebstein in 1882.

Pathogenesis of PE

Several theories regarding pathogenesis of PE have been developed over the years, but the underlying pathomechanisms have not at all been clearly understood yet. Furthermore, questions arise about the role of developmental processes in the formation of PE.

Hypertension of the diaphragm during embryonic development, intrauterine pressure on the sternum through an abnormal position of the embryo (the lower jaw of the foetus causes the deformity by pushing on the sternum), weakness and abnormal flexibility of the sternum caused by nutritional disturbance or by developmental failure, acquired chest damage caused by a permanent mechanical stress through an extreme position, given by cobblers, syphilis or rickets, a thickened ligamentum substernale which should lead to a retraction of the sternum, an imbalance between the anterior and posterior musculature of the muscle fibres of the anterior part of the diaphragm with a movement of the xiphoid and sternum backwards, have been considered as the pathophysiologic factors of PE in the past.

Today's leading hypotheses is focused on a defective metabolism in the sternocostal cartilage, resulting in a biomechanical weakness and an overgrowth of the sternocostal cartilage. A systematic analysis of the histological changes in the sternocostal cartilage of PE patients revealed a premature ageing of the cartilage. An ultrastructural and biochemical study demonstrated abnormalities in the content of trace elements in the costal cartilage from PE patients, namely decreased levels of zinc and increased levels of magnesium and calcium, and also demonstrated that the lack of zinc in the diet results in a lower metabolic activity of chondrocytes. These findings give interesting insights in the correlation of metabolic lesions and mechanical properties of the cartilage in PE.

A mechanical etiology is also considered today. Acquired chest wall depression following congenital diaphragmatic hernia repair has been reported. A study of 60 adult CDH survivors (mean age, 29 years) documented chest asymmetry in 48 and PE in 18. Depression of the chest wall and other deformities, including scoliosis, have been reported following costal cartilage graft harvesting. Mechanical etiology is also suggested by well-documented reports of PE accompanying upper airway obstruction and relieved by tonsillectomy; an infrequent cause at best, this occurrence is not relevant to the vast majority of PE patients. Further support of this mechanism is provided by another uncommon occurrence: Pectus excavatum in spinal muscular atrophy. Bach and Bianchi reported that the appearance of PE is ubiquitous in untreated infants with spinal muscular atrophy type 1, but after institution of high-span PIP-PEEP (positive inspiratory pressure and positive end-expiratory pressure), pectus resolves and lungs and chest walls grow more normally. Intrinsic abnormality of the costochondral cartilage is suggested by the occurrence of PE in patients with connective tissue disorders, such as Marfan syndrome (5- 8%), Ehlers–Danlos syndrome(3%), or Sprengle’s deformity (0.6%).

Genetics

A genetic component was identified in the 19th century in 2 reports. Coulson, in 1820, reported the occurrence of 3 affected brothers. Williams reported 50 years later on a 17-year-old with the condition present at birth whose brother and father were also affected. At that time it was of great interest that the condition was not an occupational deformity, “cobbler’s chest,” acquired from leaning over a workbench. In a series of 327 patients from 13 centers in 11 centers in North America, 43% of patients in a large series give a family history of PE, and 4% a family history of pectus carinatum. Family tree analysis has shown that inheritance has been autosomal dominant, autosomal recessive, X-linked, and multifactorial in different families.

Classification of PE

Quantification

The severity of the defect ranges from a minor degree of deformity to a severe concavity that displaces mediastinal organs. The evaluation of patients (both during preoperative and postoperative periods), has been either subjective (clinical inspection) or objective (clinical or radiological evaluation), depending on surgeon experience.

The radiological measurements that have been adopted in order to quantify PE are: First, Derveaux *et al*, using lateral chest X-rays and evaluating the relationship between anteroposterior indices at the level of the angle of Louis and those seen at the xiphoid process level, classified patients with chest abnormalities in comparison to normal individuals. Later, CT scans were used to quantify PE: In 1987, Haller *et al*, using computed tomography (CT,) created the Haller index, which is the ratio between the transverse diameter and the anteroposterior diameter, obtained from the axial tomography slice at a mediastinal window setting at the level of maximum depression. When this ratio is greater than 3.25, PE is considered moderate or severe, and surgery is indicated in order to correct the deformity. Nakahara *et al*. also conducted a study based on CT scans, numerically quantifying the depression, asymmetry, and flattening of the deformity.

As far as the clinical quantification of PE is concerned, Rebeis *et al* [10] developed an anthropometric index to quantify PE **(Fig 3-6).**

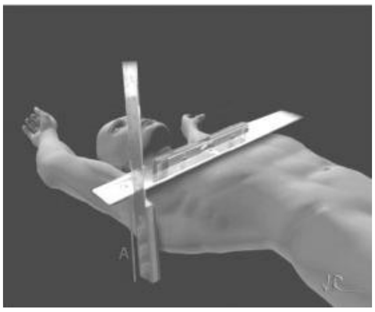


FIGURE 3. A measurement is the anteroposterior distance during deep inhaling at the distal third of sternum

FIGURE 4. B measurement is the greater depth at the distal third of sternum.

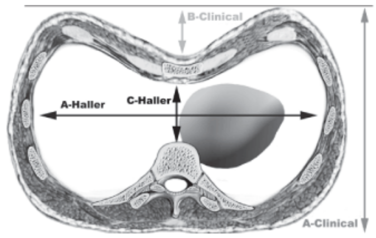


FIGURE 5. Anthropometric index=B clinical/A clinical (A=anteroposterior distance, B=depth of the deformity; Haller index=A Haller/C Haller (A=maximum latero-lateral distance, C=shortest anteroposterior distance). Both indices are calculated at the distal third of the sternum.

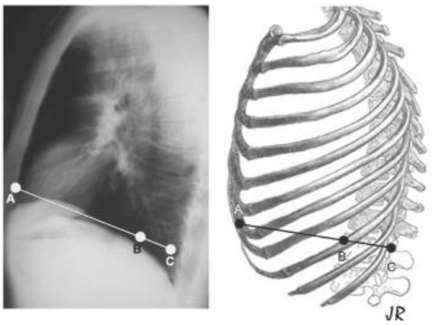


FIGURE 6. Schematic representation of the lower vertebral index (LVI). BC=vertebral sagittal diameter and AC=diameter of the posterior board of the sternum to the posterior portion of the vertebral body. LVI=BC/AC

Morphological classification

The PE condition can be classified as symmetric or asymmetric. The depression of the chest wall most frequently involves the lower sternum. The sternal notch is frequently normal or a little distorted, as are the first and second costal arches. When it is asymmetric, the major depression is almost always to the right.

Given the wide spectrum of morphologic variations of the pectus excavatum, Park *et al* [6] seeking to employ techniques tailored to each patient for optimal surgery results, created a morphologic classification system based on CT scans to facilitate decision making:

The classification begins by sorting the deformities into symmetric ("type 1") and asymmetric ("type 2") varieties:

In the symmetric types (1A and 1B), the center of the sternum (C point) and the center of the depression (P point) are located. Type 1A is the typical deep symmetrical depression of the lower sternum. Type 1B is the broad, flat symmetrical type, rather than a deep focal depression.

In asymmetric types the center of the depression is not located in the center of the sternum but is off to one side or the other. Three different types of asymmetry have been identified. In type 2A, the "eccentric type," the center of the sternum is in the midline but the maximal depression is in the cartilage off to one side. Type 2B, the "unbalanced type," describes the situation where the center of the depression is in the midline but one side of the wall of the depression is more severely depressed than the other. This creates a situation where the angles created by each wall and the vertical axis are different ($\alpha < \beta$). Types 2A and 2B can be further subdivided into focal type (2A1, 2B1) and broad-flat type (2A2, 2B2). One of the most extreme forms of eccentric varieties is the long canal type ("Grand Canyon" type, 2A3), which is a deep longitudinal groove from the clavicle all the way down to the lower chest. In the Grand Canyon type most of the depression is in the parasternal cartilage and not the sternum. Type 2C is a combination of types 2A and 2B.

Then, Robert Kelly *et al* [21] and later, Nuss *et al* [23] described the following types: Localized deep depression (cup-shaped deformity), diffuse shallow (saucer-shaped) deformity, trench-like (furrow-shaped) deformity (which is usually asymmetric), and Currarino-Silverman (mixed pectus excavatum/chondromanubrialcarinatum) (**Fig 7**). Other rare variants that Kelly *et al* have identified are illustrated in **Fig 8**. The frequency of occurrence of the different PE types is unclear, but the majority are cup-shaped; Saucer-type is far less frequent; the long trench and mixed carinatum/excavatum types are even less common. There is a tendency in some families to have similar morphology over generations. Robert Kelly *et al* highlighted that the clinical utility of careful morphologic appraisal lies in choosing preoperatively which patients will need two bars and in guiding expectations.

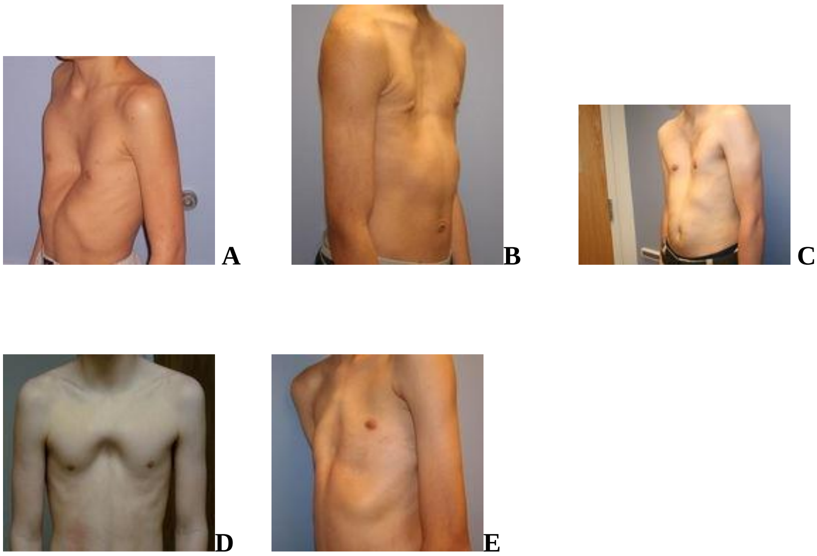


FIGURE 7. A Cup-shaped; B Saucer-shaped; C Trench; D Currarino-Silverman; E Mixed pectus excavatum/carinatum.

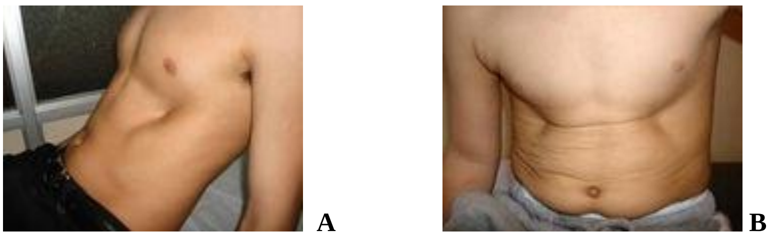


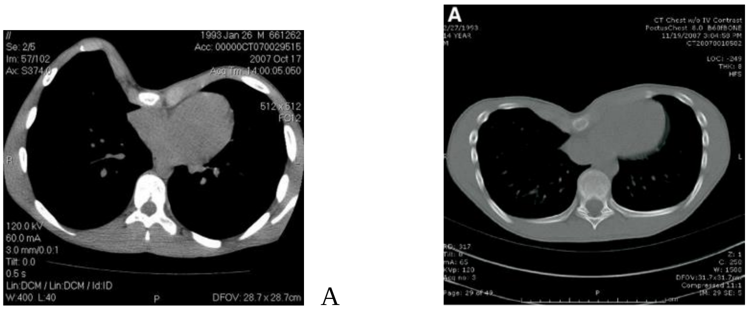
FIGURE 8. A Unilateralinferiorindentation; B Bilateral inferior indentation.

Clinics, labs

Symptomes, physical findings

The antenatal diagnosis of PE has been reported, but it is rare. Most patients have the deformity throughout their childhood life and it worsens during the teenage growth spurt Systemic effects of the deformity range from otherwise asymptomatic presentation to exercise intolerance that necessitates surgical treatment. PE is associated with a typical posture; thin, tall patients with a pot-belly and forward-drifted shoulders, which could lead to permanent scoliosis. Female patients may present with markedly asymmetric breast projection.

Depending on the severity of PE, deviations of thoracic organs and spine deformities are known: The depression of the sternum can displace the heart and reduce the lung volume. However, in a deep chest, the heart may not be compressed despite the significant depression of the anterior chest wall observed clinically (**Fig 9**). CT scanning demonstrates this and explains why reports vary in their “effect on the heart. More or less severe clinical signs as a result of the anatomical changes may occur: Chest pain, perceived limitation of exercise ability, fatigue, dyspnoea on exertion, respiratory infections, asthma symptoms, palpitations or heart murmurs. Even a single case report of syncopal symptoms has been reported. However, PE in most instances has little or no influence on the function of the inner organs, and symptoms affecting daily life activities are either rare.
The pulmonary and cardiovascular functions of patients with PE deformities have been analyzed in many studies and have revealed measurable deficiencies but it remains a matter of debate if there is an improvement of pulmonary and/or cardiovascular symptoms after surgical correction (see article review topic).



A B

FIGURE 9. (A) no heart compression; (B) heart compression

Pulmonary function studies

Efforts to dissect the cause of exercise intolerance have led to studies of pulmonary function. Spirometry shows air flow out of the chest on exhalation at rest usually 10% to 20% below the expected average for the population [FVC (forced vital capacity), FEV1 (forced expiratory volume) and FEF (forced expiratory) are below the predicted value] (**table 1**). Plethysmography shows that lung volumes are similarly modestly decreased. It is believed that although the decreases in air flow in and out of the chest in a primary (not recurrent) PE are understandably modest, they do contribute to the exercise intollerance and the measured diminutions of exercise capacity that is revealed by the exercise tests during the pulmonary function studies.
In patients with recurrent PE, significant restrictive disease is found, with spirometry about half of predicted values.

Table 1 Pulmonary function tests from a multicenter study of pectus excaratum. [21]

	Number	Mean % of predicted	IQR 25th, 75th percentile	*P* of difference from 100%
FVC all ages	307	90	[81,98]	<0.0001
FVC <11	47	92	[83,100]	<0.0001
FVC <11	260	89	[81,98]	<0.0001
FEV1 all ages	305	89	[79,96]	<0.0001
FEV1 <11	47	92	[85,98]	<0.0001
FEV1 <11	258	88	[79,96]	<0.0001
FEV1/FVC, all ages*	305	86	[81,91]	Not applicable
FEF25-75 all ages	303	85	[69,100]	<0.0001
FEF25-75 <11	47	89	[76,105]	<0.01
FEF25-75 <11	256	84	[68,98]	<0.0001
TLC all ages	217	94	[85,102]	<0.0001
RV all ages	218	111	[86,133]	<0.0001
RV/TLC, all ages*	217	26	[22,31]	Not applicable

*Except for these, all mean values expressed as percent predicted.
Abbreviations: FVC, forced vital capacity; FEV1, forced expiratory volume in 1 second; FEF25-75, forced expiratory flow from 25% to 75% of expiration; RV, residual volume; TLC, total lung capacity.

Cardiology evaluation

The hemodynamic effects of PE have been the subject of numerous reports and much controversy. The amount of right atrial and ventricular compression varies with the overall shape of the chest**.** Cardiology evaluation including electrocardiogram and echocardiogram is important, because a fraction of patients will have findings of right atrial and ventricular compression, mitral valve regurgitation or mitral valve prolapse as a direct consequence of compression. For the ventricle compression Coln *et al* [40] demonstrated that 95% of the studied patients had cardiac compression. Arrhythmias, including first-degree heart block, right bundle branch block, or Wolff–Parkinson–White syndrome, were also present.

In severe cases of right heart compression, the stroke volume is diminished as demonstrated by direct cardiac catheterization, oxygen saturation studies, CT scanning, and echocardiogram.

Radiology evaluation

The CT scan helps make the judgment of when to proceed with surgery more objective**.** Since morphology varies, preoperative imaging for anatomic assessment and documentation of dimensions of the chest are important. Often the pectus radiographic index (measured as internal thoracic diameter from left to right divided by the distance from the back of the sternum to the front of the vertebral body) is smaller than the absolute depression would suggest clinically. CT shows the deformity and the degree of cardiac compression and displacement clearly and the degree of lung compression,. Echocardiogram may make no notation of right heart compression even when it is obvious on CT. Moreover, the CT scan shows other unexpected problems (ex. previously unrecognized atelectasis).

Review of the CT scan with the patient and parents before surgery helps enormously to communicate the extent of deformity and to form expectations for hospital course and final result.

Body image

During adolescence, body image is of great importance. Precisely when the person is establishing an independent identity, choosing a trade, and beginning involvement with the opposite sex, he or she is afflicted with a deformity that reduces his capacity to do those things.

Concern about the appearance of the chest prompts many, if not most, patients to have the operation. The cosmetic appearance of the patients can be so affected that it may lead to relevant social discrimination, especially during adolescence, and socio-psychological problems like avoidance of social interactions and poor self-image. The psychological impact of a pectus deformity often results in significant reduction of quality of life. Robert E. Kelly Jr [21] sought to quantify psychosocial functioning with psychometrically sound assessments, and to detect the effects of surgical correction of PE. Thus, a test for body image effects specific to PE was developed and validated. An enormously important finding was that severity of the depression by CT scan did not correlate with the patients' or parents' perception of body image concerns. A multicentre study [41] demonstrated that the surgical repair of PE patients improves these socio-psychological problems. Surgeons should take the position that severe PE is a significant deformity, not a cosmetic glitch, and it must be treated. Surgical treatment for a severe case should not be withheld because a pediatrician fails to understand the importance of the deformity to the child and parents. Besides, surgical correction of primary PE has recently been demonstrated to carry low operative risk at several centers across the world.

Indications for PE treatment

Evidence indicates that both pectus excavatum and carinatum deformities worsen with age. Consequently, the majority of these patients should undergo surgical repair during childhood and early adolescence. However, there is a significant number of patients who progress to adulthood without surgical repair with persistent and often worsening symptoms because of loss of flexibility of their previous pliable pediatric chest wall. Studies have shown that the indications for surgical repair of pectus defects in adults are similar to those reported for pediatric patients.

Criteria for surgical repair

Determination of a severe pectus excavatum and the need for repair include 2 or more of the following criteria, as established by Croitoru *et al* [15]:

(1) a Haller CT index greater than 3.25

(2) pulmonary function studies that indicated components of restrictive or obstructive airway disease

(3) a cardiology evaluation in which the compression causes mitral valve prolapse, abnormal rhythm, murmurs, displacement or conduction abnormalities on the echocardiogram or EKG.

(4) documentation of progression of the deformity with associated subjective symptoms other than isolated concerns of body image
(5) previous failed Ravitch procedure or failed minimally invasive procedure.

The criteria established by Kelly [21] are those of Croitoru *et al,* but body image disturbance is an additional criteria.

History of PE treatment

"Fresh air, breathing exercises, aerobic activities and lateral pressure" were prescribed for the condition. Even to the present time, various exercises, efforts to improve posture, and braces such as a "figure of eight" clavicular fracture splint have been employed. No critical studies of their effectiveness have been identified. The most established treatment options of PE are surgical interventions. The operations developed can be devided in the following groups:

Year 1911-1920: Rib and cartilage resection, sternotomy

1920-1940: Costal cartilage resection and sternal osteotomy with external traction

1940-1949: Costal cartilage resection and sternal osteotomy without external traction.
The various forms of external traction were abandoned because they were cumbersome, impra impractical, and worst of all, gave rise to lethal infections in the preantibiotic era.

1949: Costal cartilage resection with internal support. Widely adopted.

1954: Turn over techniques.

1998-: No resection, only internal support

More specifically:
Before advances in endotracheal intubation in the first World War, which allowed ventilation of the patient with an open pleural cavity, only limited operations on the chest could be performed. The first reported attempt at surgical correction was made in 1911 by Meyer, who removed the 2nd and 3rd costal cartilage on the right side without improvement of the deformity.

Next, Sauerbruch, one of the pioneers of thoracic surgery, used a more aggressive approach in 1913, by excising a section of the anterior chest wall, which included the left 5th to 9th costal cartilages as well as a section of the adjacent sternum. By the 1920s, Sauerbruch performed the first pectus repair using bilateral costal cartilage resection and sternal osteotomy. He also advocated external traction to hold the sternum in its corrected position for 6 weeks after operation. The Sauerbruch technique, had the disadvantages of causing paradoxical respiration, leaving the heart unprotected and giving a poor cosmetic result.

In 1939, Ochsner and DeBakey, noting the high mortality of methods that involved significant chest wall resection, advocated limited resection.

In the same year, Lincoln Brown of San Francisco published his experience with two patients, and suggested that all that was necessary to correct the deformity was to divide ligaments attaching the sternum to the diaphragm. Although clearly disproven by thoracoscopy, the notion that short diaphragmatic attachments pull the deepest part of the sternum inward persisted for almost 60 years and received comment by many authors.

Mark M. Ravitch made great contributions to the management of PE. Before about 1950, surgical treatment carried significant risk of death and few patients were referred for operation. Ravitch contributions started with his 1949 report [42] on a novel technique that included bilateral subperichondrial costal cartilage resection, sternal fracture, complete detachment of the sternum from its attachments below the 2nd or 3rd costal cartilage including the rectus abdominus, all intercostals muscle bundles and costal cartilage perichondrial sheaths, and placement of a substernal bone graft to elevate the sternum. The overall success of this approach led to its wide adoption; the Ravitch procedure is performed in some cases even today.

Sternal turnover was a totally new concept introduced in 1954 by Judet. In 1970, Wada *et al* [43] reported a large series: They removed the whole deformed sternum, turned it over, and sutured it back in place. This procedure was not widely adopted outside Japan because of major complications in the event of infection and sternal necrosis.

Since 1950, the open procedure of cartilage incision or resection, sternal osteotomy, combined with a variety of forms of internal fixation had been a standard in the treatment of PE. However this procedure was complex, with prolonged operating time and considerable blood loss, a significant complication rate (cardiac perforation , laceration of the phrenic nerve, migration of the PE correction bar placed at open operation into the endo-myocardium, left ventricle, or abdomen), a non trivial failure rate of 5% to 36% (unsatisfactory results), a recurrence rate of 2% to 20.5%, a large anterior operative scar [44-48]. Instability of the chest wall due to wide cartilage resection had also been reported. Besides, in cases of too extensive (five or more ribs on its side) cartilage resection in very young patients (<4 years), experienced asphyxiating thoracic chondrodystrophy (labeled as"acquired Jeune's syndrome" by authors), as described by Haller *et al* [49]: The rib growth was impaired (parents typically said that the chest did not appear to enlarge after operation with the general body growth) and caused restrictive ventilatory deficit.

Just after several reports had highlighted difficulties with the open operation, Nuss and his associates developed a minimally invasive technique to correct the depression of PE that remodeled the sternum with no costal cartilage resection or sternal osteotomy but with a substernal bar alone. The rationale for this technique, which was published in 1998, rested on three observations: 1) Children have a soft and malleable chest: Their chest is so soft that even minor respiratory obstruction causes several sternal traction, and a trauma rarely causes rib fractures, flail chest etc. Moreover, the American Heart Association recommends "using only two fingers" when performing CRP in younger children and "only one hand in older children" for fear of crushing the heart.
2) Reshaping of the chest happens even in older adults with emphysema, who develop a "barrel chest" **(Fig 10)**.
3) The role of braces and serial casting in the treatment of skeletal anomalies such as scoliosis, club-foot, and maxillomandibular malocclusion by orthopedic surgeons is well established. Besides, in pectus excavatum it is not the bones but the cartilages that are deformed. Since the Nuss procedure was presented in 1998, it has been widely accepted.

FIGURE 10 X-ray of a patient with emphysema showing anterior bowing of sternum. [27]

Other recent minimally invasive technique is the so-called "Erlangen technique" [50]: The sternum is mobilized initially by retrosternal dissection via an anterior incision, and an elastic metal bar is implanted transsternally through stitch incisions. Minimal resection of the cartilages is provided by intraoperative tensiometry **(Fig 11)** . This technique measures, at defined intervals, the necessary forces to elevate the chest wall and determines up to what point cartilage resection is necessary and whether complete division is necessary. The metal bar will be removed after a year.

FIGURE 11. Intraoperative tensiometry.

The magnetic mini-mover procedure [20],[51], uses magnetic force to pull the sternum forward: An internal magnet that is implanted on the sternum and an external magnet of a nonobtrusive custom-fitted anterior chest wall orthosis produce an adjustable outward force on the sternum. A metal plate is brought behind the sternum used as a counter-support for the magnet which will be placed on the sternum. The operation needs general anaesthesia, but it is possible that patients can leave the hospital at the same day of surgery. Outward force is maintained until the abnormal costal cartilages are remodeled and the pectus deformity is corrected. Outcomes will be reported upon the completion of the phase II clinical trial.

Other worthmentioning operational techniques for the correction of PE wall are the method of Leonard and the method of Robicsek which both represent modifications of the Ravitch operation [20]. In the approach of the Leonard modification , a curvilinear incision is made over the sternum and after mobilization of the pectoral muscles the lower costal cartilage is removed, whereas the perichondrium is left in space. A wedge osteotomy is performed and instead of a bar there is a wire placed behind the sternum which is pulled up through separate stab incisions fixed to an external brace. The brace is worn for about 3 months [20]. During the method of Robicsek *et al* [56] there is conservative bilateral sub-perichondral resection of the defective costal cartilages and detachment of the xiphoid process; next a transverse sternotomy is performed at the upper level of the deformed sternum, which is then bent forward; the corrected sternal position is secured by a “hammock” of synthetic mesh, spread behind the sternum, and attached to the respective cartilage remnants. The pectoralis muscles are then united presternally.

There is one surgical treatment of Pectus excavatum via sternochondroplasty introduced by Lacquet without the use of prosthetic material and with good long-term results. In a recent survey, the sternochondroplasty is described to be superior to the Nuss procedure in the cases of asymmetric PE.

Moreover, plastic surgeons have treated PE with techniques like implantation of silicone bags or artificial skin in the depression and lipofilling. It is the external contour of the chest that is restored, but the shape of the chest wall itself is not remodeled [20].

A non-surgical alternative method in the treatment of PE represents the Vacuum chest wall lifter [24],[35]. It was developed and tested by an engineer who had pectus excavatum (EK, third author); he developed this device as an attempt to avoid surgery. This device is applied to the chest depression and is created by a suction cup that becomes activated by the patient with a hand pump, creating a vacuum at the chest wall of up to 15% below atmospheric pressure. It has four different applications: As an alternative method to the surgical treatment for the repair of PE in less severe cases; it may be useful in the preoperative preparation for open or less invasive techniques, because it looses connective tissue facilitating subsequent repair; it may be used if a bar has to be removed earlier than scheduled in order to stabilize, maintain, or even improve the surgical result; finally, it can be used during the Nuss procedure for elevation of the sternum (as it will be described in the Modified Nuss procedure chapter).

Original Nuss procedure

The first minimally invasive pectus repair (MIRPE) was developed by Nuss and his co-workers. The new technique and the results obtained over a 10-year period were first presented at the May 1997 American Pediatric Surgical Association and a year later were reported on in the Journal of Thoracic Surgery [19]:

Bar insertion

From 1987 to 1996, 42 patients with PE under age 15 were treated by the new technique. When the minimally invasive procedure was first introduced, it was reserved for prepubertal patients, and the standard procedure was used for the older patients. However, starting in 1994, the minimally invasive procedure was performed in teenagers also.

Technique

The patient's chest was measured before surgery, and the correct length steel bar(s) selected and bent using bar benders. All patients were given a 2-day course of cefazolin (Ancef) starting at the time of surgery. The operation was performed under general endotracheal anesthesia with muscle relaxation. The patient was positioned with both arms abducted at the shoulder (90o in relation to the body) to allow access to the lateral chest wall. When the patient was draped, the previously selected steel bar was placed on the patient's chest and bent into its final convex shape to conform to the desired anterior chest wall curvature. To save operating time, the bar was bent into its rough configuration before surgery, but final molding was done during the operation because the bar had to fit snugly. It was necessary to exaggerate the curvature slightly to allow for anterior chest wall pressure. The surgical steel bar used in the last years (Walter Lorenz Surgical, Jacksonville, FL) was considerably stronger than the one used 10 years before. Two lateral transverse incisions 2.5 cm long were made between the anterior axillary and posterior axillary lines(a). A skin tunnel was raised anteriorly, and the previously selected intercostal space was entered with a 30-cm long curved Kelly clamp. The Kelly clamp was slowly advanced across the mediastinum immediately under the sternum until it emerged on the opposite side. The clamp was advanced to the handle to enlarge the tunnel. Two strands of umbilical tape were pulled through the tract. One strand of umbilical tape was then used to guide the Kelly clamp in from the opposite side. When the track was deemed wide enough, the previously prepared 1.5.cm wide and 2-mm thick surgical steel bar was pulled beneath the sternum using the umbilical tape for traction. The bar was passed under the sternum with the convexity facing posteriorly. When the bar was in position, it was turned over with a vice grip so that the convexity faced anteriorly thereby raising the sternum and anterior chest wall into the desired position. (**Fig 12**). A second bar was placed superiorly or inferiorly if needed. The bar was secured with heavy sutures to the lateral chest wall muscles. If the bar was unstable, a 2- to 4-cm crossbar was attached to one or both ends of the bar. When two bars are used, the two ends may be linked together with crossbars to form a rectangle **(Fig 13).** Before closing the incisions, positive end-expiratory pressure (PEEP) of 4 to 5 cm Hz0 was added to prevent pleural air trapping. The wounds were closed in layers.

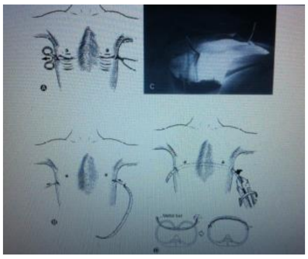


FIGURE 12. (A) Long curved Kelly clamp advanced across mediastinum. (B) Diagram shows convex steel bar being guided into the substernal tunnel using unbilical tape to keep it on track. (C) Pectus bar positioned deep to sternum with concavity facing posteriorly and umbilical tape still attached to one end. (D) Diagram shows steel bar in the process of being turned over.

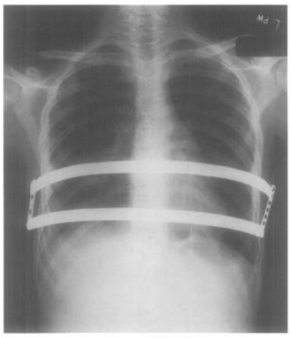


FIGURE 13. When two bars were used, the two ends may be linked together with cross bars to form a rectangle.

A chest radiograph was obtained in the operating room to check for pneumothorax.
Operating time was much shorter than for the standard procedure. Blood loss was minimal, ranging from 10 to 25 ml for an average of 15 ml (compared with the 300 ml average blood loss for the standard procedure). No patient required transfusion. Air trapping in the pleural cavity was minimized by using positive end expiratory pressure toward the end of the procedure.

Pain management and ambulation

Care was taken so that the patient would emerge from anesthesia slowly with adequate sedation and pain control to prevent postanesthesia agitation. Postoperative epidural anesthesia besides the usual sedation was used in the last five patients with good results.
The average length of hospitalization was 4.3 days. Patients were discharged from the hospital when able to walk unaided. The duration of hospitalization was directly dependent on age-the younger the patient, the shorter the hospital stay, with some patients being discharged on the third hospital day. During the first 2 weeks after surgery, the children were kept at rest either in the hospital or at home. Thereafter, they were given permission to slowly resume mild exercise, and they were permitted to resume their usual activities whenever they were fully recovered, usually at the end of 30 days.

Early and later complications:

Small residual pneumothorax, which resolved spontaneously in 24 hours in three patients; Bilateral pneumothorax occurred in a 15year-old trumpet player 2 months after bar insertion and responded to tube thoracostomy; Bar displacement requiring revision in two cases; Skin irritation that occurred when the bar was too soft and tended to straighten out; Wound infection that resolved with antibiotics and did not necessitate removal of the bar; Postoperative viral pneumonia that responded to supportive care **(Table 2).**

Table 2 Complications in 42 Patients Undergoing Minimally Invasive Procedure.

Complication	No of patients
Pneumothorax	4
Skin irritation	4
Bar displacement	2
Wound infection	1
Viral pneumonia	1

Follow-up

Mean follow-up from the time of bar insertion was 4.6 years.

Bar removal

The main challenge was in maintaining the correction long enough for it to become permanent. Using information gleaned from other orthopedic conditions, such as the conservative management of club foot, scoliosis, and orthodontic surgery, it was decided that the bar would be left in place as a splint long enough for the new chest configuration to become permanent. So, two or more years later, the bar was removed under general anesthesia on an outpatient basis. The patients were seen at yearly intervals thereafter. Mean follow-up from bar removal was 2.8 years.

Results

The patients have been examined and photographed 1 year after bar removal. Based on the photographs, the patients were graded as follows: excellent (normal chest), good (mild residual pectus), fair (moderate residual pectus) and poor (severe recurrence requiring further treatment).

Of the 30 patients who have had their bar removed, 22 patients have had an excellent result and 4 patients had a good result while 4 patients had a fair or poor result. The fair and poor results occurred early in the series because: 1) Three patients had recurrence because the bar was too soft to maintain normal sternal position and bent under pressure. The subsequent use of a stronger bar prevented this problem. 2) In a patient with Marfan's syndrome, the sternum was not strong enough to maintain the initial good result; it simply collapsed above and below the metal bar. This would not have occurred if two bars had been used. 3) In one patient with complex thoracic anomalies the bar was removed too soon. The patient initially had excellent correction of his pectus excavatum, but at 6 months he appeared to have a a mild carinatum, so his bars were removed; Over the next year a partial recurrence of his pectus excavatum was developed. As a result of this experience, leaving the bar in place for 2 years or longer was decided.

Conclusion

Since 1950 cartilage incision or resection, sternal osteotomy, combined with a variety of forms of internal fixation had been widely used as the procedure of choice. However, this standard procedure was long and complex with considerable blood loss, a significant complication rate, and a nontrivial failure rate of 5% to 36%. Compared to the standard procedure at that time, the Nuss procedure seemed to have major advantages: (1) No anterior chest wall incision, no need to raise pectoralis muscle flaps, and no need to resect rib cartilages or perform sternal osteotomy; (2) short operating time, minimal blood loss, and early return to full activity; (3) normal long-term chest strength, expansion, flexibility, and elasticity; and (4) excellent long-term cosmetic result especially since increasing the strength of the steel bar and inserting two bars when necessary.

Modified Nuss procedure

Having significant advantages, the Nuss technique was immediately adopted and became widely accepted. As time passed, more and more patients were operated on. Although it was clear from the beginning that the Nuss procedure had great benefits compared to the older techniques in terms of results and safety , there has been continuous interest by surgeons for technical improvements to make the procedure even safer and more succefull. Every time that a complication has been identified, preventative measures have been instituted

In the same year that the Nuss procedure was first published and four years later, Nuss and his co-workers at the "The Children's Hospital of The King's Daughters, Norfolk, VA" reported major changes made since the technique had been first performed [27] [15]:

1) Selection of patients. Initially, the technique was limited to younger prepubertal patients but later that the success achieved with young patients was clear, it was offered to older patients as well. Patients even over 20 year old were treated with the Nuss technique in various institutes. The tallest patient treated was 6 feet inches tall. The only limitations in terms of the patient size was the chest diameter, because the longest bar was 16 inches.

2) Routine use of thoracoscopy. Although the thoracoscopy had been utilized on occasion for this technique, it started to be performed routinely only after a case of cardiac perforation (b). A 3-mm or 5-mm thoracoscope was used. After two lateral skin incisions had been made and skin flaps had been raised anteriorly to create a pocket for the edges of the bar, a thoracoscope was inserted through the lateral chest wall, 2 interspaces below the lateral wall skin incision. The skin incision was retracted anteriorly to allow visualization of the intercostals space and the Crawford clamp/introducer was inserted and advanced across the mediastinum under thoracoscopic guidance. At the end of the procedure, after fascial closure of the thoracic incisions and before removal of the thoracoscopic trocar, the CO_2 insufflation tubing is cut and placed into a bowl of normal saline, creating a water seal. The anesthesiologist applied positive pressure ventilation, and 5-mm positive end-expiratory pressure (PEEP) until the accumulated CO_2/air had been expressed as confirmed by cessation of the bubbling or by reinsertion of the thoracoscope. This way the residual gas/ air is evacuated decreasing the risk of pneumothorax. The thoracoscope is inserted preferentially from the right side, because the heart in severe pectus deformities often is displaced into the left thorax and obscures the view. In all but a few cases, the entire field of dissection can be visualized from the right, and, in cases in which the depression prevents visualization to the left side, left thoracoscopy or bilateral thoracoscopy was used. The thoracoscopy allowed direct visualization of the mediastinal structures, clear visualization of the substernal tunnel and proper placement of the clamp making the procedure much safer.

3) Selection of a curved Crawford vascular clamp to replace the Kelly clamp for the creation of the substernal tunneling. Later, the Kelly clamp was replaced by an introducer/dissector. This instrument that is used up to date, not only creates the substernal tunnel but elevates the sternum before the insertion of the bar as well. Elevation of the depressed sternum before bar insertion became possible because of the strength of the new introducer. After passage of the introducer across the mediastinum, the anterior chest wall could be elevated carefully out of its concave position by lifting the introducer on each side of the chest, thereby correcting the pectus excavatum before bar insertion. This elevation of the anterior chest was repeated several times until the sternum was raised to its desired position. The introducers range from small to extra large and have varying degrees of curvature to assure that the blunt tip is able to "hug" the underside of the sternum and avoid pericardial injury. The introducer also can gently dissect the pericardium away from the sternum and has an eyelet for threading an umbilical tape. Moreover, the use of an introducer that makes a smaller opening into the chest in contrast to a large Kelly or Crawford clamp decreased the risk of residual pneumothorax that was common during the original procedure.

4) A new bar rotational instrument. Rotation or "flipper" instruments **(Fig 14)** replaced the vise grip once used to turn the bar over. These devices were designed to offer more torque with less resistance when turning the bar into position.

5) New crossbar (stabilizer) to prevent bar displacement. The bar inserted was held in position with numerous heavy absorbable mattress suture that pulled the lateral thoracic wall tissues over the bar, and whenever there was question regarding its stability, the newly developed crossbar-stabilizer was used to prevent it from shifting, in addition to the sutures. Subsequently, a wired lateral stabilizer in 2 sizes was developed to be used routinely. This wired stabilizer was prevented from sliding off the bar, by a number 3 surgical steel or a 18-gauge Luque wire in a figure-of-eight pattern.

6) New bars: It became stronger, with round edges for safer insertion, more and larger holes for easier suture placement and more serrations to promote scar tissue formation and to help with wire fixation of the stabilizer.
7) Careful attention to the EKG to avoid cardiac perforation(i). The EKG volume was set at maximum so as to be clearly audible during insertion of the Crawford clamp across the mediastinum. Any ectopy caused immediate cessation of onward progression and checking with the thoracoscope for possible bleeding. If there was none, the surgeon increased the anterior elevation of the sternum, and slowly advanced. If the pectus was so severe that one could not get the clamp across the mediastinum without causing repeated ectopy, he moved down one interspace. Inserting the bar through this lower interspace end elevating the sternum usually allows access to the original track without difficulty.
8) Thoracic epidural analgesia as a routine. Thoracic epidural analgesia was utilized routinely for postoperative pain management for 2 to 4 days.
9) Postoperative activity. Initially regular activity was permitted four weeks after surgery, and in the 2002 report it was suggested that patients should return to all normal activities at two months postoperatively.

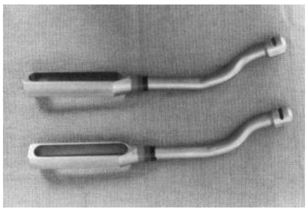


FIGURE 14. Bar rotational device, or "flipper."

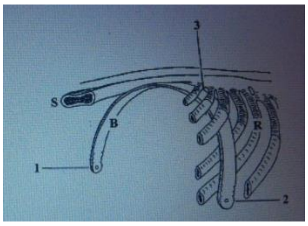
Results: The initial bar displacement rate was 15% , after the introduction of the stabilizer it dropped to 5,6% and after the introduction of the wired stabilizer it dropped to 5%. Long-term results after bar removal were excellent in 71.8% of the cases, good in 19.7% of the cases, and the surgery was considered failed in 8.5% of the cases.[15]

In the meantime, in 2000, Engum *et al* [32] proposed a modification to the Nuss procedure concerning patient's arms position.
Technique: Practically, the standard technique as known at the time was performed, but the patient's arms instead of being abducted they were at his side while a blanket under the back produced a slight elevation of the chest to expose the sides of the chest bilaterally. Thoracoscopy was not used as a routine. According to authors, "if the surgeon approaches the lateral sternal margin of the pectus excavatum on the flattened hypoplastic side, the risk of cardiac injury should be low."

The additional use of a lateral stabilizing bar had improved stability but had not eliminated the occurrence of bar displacement. Thus, in 2001 Hebra *et al* [14] described another strategy against the risk of bar shifting, which involved fixation of the bar with placement under thoracoscopy and via a spinal needle that passed through a single 3mm stab wound, of a nonabsorbable suture next to the sternum, that encircled a rib and the bar (**Fig 15**).

Technique: The standard MIRPE with thoracoscopy is performed. Thus, the pectus bar is passed, rotated and positioned in the anterior mediastinum under thoracoscopic guidance. At that point, the bar is secured by placing the sutures for the first two (standard) points of fixation (**Fig 15.1**). Typically, absorbable sutures are placed between the bar and the muscle fascia on the left side and nonabsorbable sutures on the right side. Next, the location for the third point of fixation is identified and a small 3mm skin incision is made, typically on the right of the lateral sternal margin at a point where the pectus bar crosses (overlaps) a cartilage rib, away from the internal mammary vessels. The third point fixation can be identified easily by placing the thoracoscope next to the bar and against the anterior chest wall, so that the light from the scope will transiluminate through the chest wall. With the room lights dimmed, one can see the pectus bar and its relationship to the ribs. Through this skin opening, an 18-gauge spinal needle is introduced into the right pleural cavity, above or below a rib, as close as possible to the pectus bar, as illustrated in **Fig 15.2**. With the needle in place, a 0-Prolene suture (Ethicon, Somerville, NJ) is passed through the needle into the chest, under thoracoscopic guidance. The needle is then removed leaving the Prolene suture in place. Using the same skin incision, a 3-mm laparoscopic grasper is passed, this time over the opposite margin of the rib (opposite margin where the Prolene suture was introduced), again as close as possible to the pectus bar, as illustrated in **Fig 15.3**. Under thoracoscopic visualization, the 3-mm grasper is used to grab the Prolene suture and retrieve it back to the outside . With this maneuver, the Prolene suture will encircle one rib and the pectus bar (**Fig 15.4**), creating the third point of fixation. The suture is tightened and several knots are placed and buried under the skin. The small skin incision is closed with absorbable subcuticular suture. This technique does not preclude the use of a lateral stabilizer if additional reinforcement to the fixation of the bar is felt to be necessary (particularly recommended for teenaged patients).

In the authors series, bar displacement occurred early in the series in one patient (5%) , because an absorbable suture was inadvertently used for the third point of fixation. Result analysis of the authors series, showed that this modification creates an additional third point of fixation of the pectus bar to prevent displacement (creates a 3-point fixation system), it can be applied even to teenaged patients, it does not add any significant time or cost to the operation, and it is fairly simple to perform.



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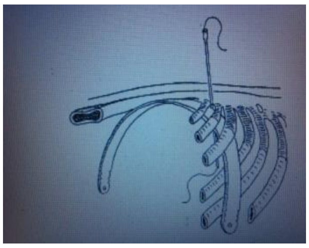
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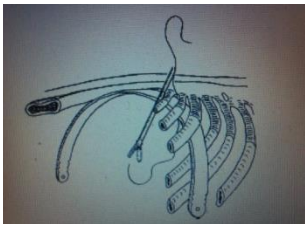
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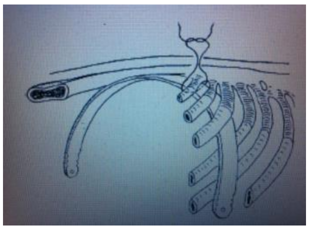
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FIGURE 15.
1. Three-dimensional illustration of the concept that 3 fairly equidistant points of fixation of the curved pectus bar provide the ideal geometric distribution of the necessary support to prevent bar displacement after surgery: Points 1 and 2 represent the standard points of fixation originally described,;Point 3 represents the location for the “third point of fixation.” (S=Sternum; B= Bar; R=Rib cage).
2.Through a small skin incision made at a point at which the pectus bar and one rib overlap, lateral to the sternum, an 18-gauge spinal needle is introduced into the right pleural cavity, as close as possible to the pectus bar. A Prolene suture is passed through the needle into the chest under thoracoscopic visualization.
3. A 3-mm laparoscopic instrument is used to grab the Prolene suture. Note that the instrument is passed through the same skin incision but in the opposite margin of the rib and pectus bar to allow the suture to encircle the rib and the bar.
4. After the Prolene suture is tightened, it will firmely encircle the bar around one rib, lateral to the sternum, creating the so called “third pointnfixatioin of the pectus bar. The knot is easily buried under the small skin incision on the anterior chest.

Early use of the Nuss procedure was limited to children with symmetrical pectus excavatum, while asymmetric cases and adults were not treated with the Nuss procedure. In adults, a conventional single bar had failed to elevate the heavy chest due to loss of the arc and consequently both tips of the bar separated from the lateral chest wall at the hinge points. In asymmetric types, the standard symmetrical bar could not elevate the depression to the target level without excessive protrusion of the other side. Therefore, Park and his colleagues [6] developed technical modifications to correct virtually all varieties of pectus excavatum including patients with asymmetric varieties and to extend the procedure to adults.

Technique: 1) Bar shaping for each PE subcategory. An appropriate sized bar was selected. Bar size was determined by the length between bilateral midaxillary lines, and the points corresponding to the C and P points were marked on the bar. The bar was then shaped at the operating table to account for the morphologic type of pectus (**Fig 16-17).** An asymmetric bars corrects asymmetric types of pectus, causing maximal elevation pressure on the deepest point of the depression (point P) wherever it is located.

For type 1 (symmetrical) pectus was used a bar that was manufactured and shaped symmetrically with the C point in the center as the original Nuss bar. Then, the surgeon bent each side of the bar more than the center to create a bridge shape. In surgeon’s hands this eliminated a problem of the original Nuss shape that often resulted in overcorrection.

For type 2 (asymmetric) pectus an asymmetric bar based on the morphology of the pectus has been created: For type 2A pectus, a bar that placed the maximum convexity of the bar corresponding to point P was chosen. In type 2B a portion of the chest (the E point) is already elevated; thus the important part of the technique for this variety is to inhibit the further elevation of this area. For type 2B or type 2C (the combined type), a seagull shaped bar was made by creating a notch in the bar corresponding the point of chest protrusion (E point). The function of the seagull shaped bar in combination with the crest compression technique is that the protruded rib (E point) becomes the hinge-point on that side, which tends to depress that point instead of elevating it.

For adult patients additional modifications in the shape have been made. To facilitate more central elevation, a “hump-shaped bar” was designed to include a segment of exaggerated central convexity. This design provides more resistance to pressure. The stiffness can be further enhanced as necessary to a “compound bar” by placing a smaller central arc between each hinge-point and adjoining at either side by two larger arcs (D > D′). To place part of the depression (P point); it is not necessarily the center of the sternum (C point) that should be elevated. the retrosternal bar exactly at the bottom of the depression, the bar can be placed obliquely using different levels of hinge-points in order to achieve better correction. The concept of the compound bar is a circle with a smaller diameter bearing a heavier load. The compound bar simultaneously resolved the most difficult issues, namely the smaller central arc makes the bar convex enough to elevate the depression and the larger lateral arcs can adjust the width of the bar easily to fit the size of the chest. In conclusion, the central concept of this technique is the recognition of the point to be elevated. That point is the deepest point and not the centre of the depression.

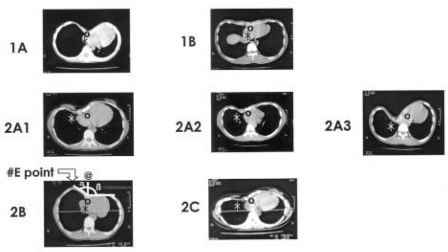


FIGURE 16. Computed tomography scans of various morphologic types of pectus excavatum. O=center of the sternum (C point); *=center of the depression (P point); #=protruded point of chest wall (E point); @=angles of each chest wall are different (a<b).

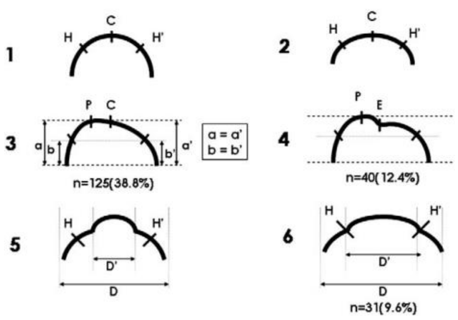


FIGURE 17. Various shapes of the Nuss bar. (1) Classic. (2) Bridge. (3)Asymmetric. (4) Seagull (5) Hump. (6) Compound. (C=center of the bar; D=diameter of the circle; E=elevated point of the sternum; H=hinge points; P=deepest point of pectus.)

2) Two bars: In cases of broad or long depression such as the Grand Canyon type, the parallel bar technique is applied. Two bars are inserted at superior and inferior levels parallel to each other (parallel bar technique). For larger adults a double bar can be made by affixing a 2-inch smaller supplementary bar to inside of the main bar (c).
3) The Five-Point fixation **(Fig. 18)** to avoid rotation or displacement of the bar without a stabilizer. It can be applied as a routine. This technique fixes the bar at five points: At both ends of the bar, steel wires encircle the rib above and the rib below, each wire passing through the end-hole of the bar. A fifth wire is added on the right side at the hinge-point, which encircles the bar and a rib together. The pericostal wire sutures are placed by piercing the skin over the ribs as it is not possible to place them through the lateral incisions. Once placed percutaneously, the ends of the pericostal wires can be easily accessed by subcutaneous dissection through the skin incision and knotted to the bar. This maneuver makes possible to do all necessary pericostal sutures through the single tiny incision on each side, even in the parallel bar technique where there are as many as seven or eight pericostal wires.

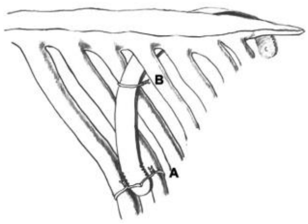


FIGURE 18. Five-point fixation technique. View of the anterior portion of the right thorax: (A)=end hole fixation technique; (B)=hinge point fixation on the right.

The authors, noted that bar displacement occurred more frequently in the severely asymmetric pectus or adult patients and identified various mechanisms for it: 1) Flipping, which is the most common mechanism, is a rotation of the bar as it pivots on the hinge-point. 2) Lateral sliding of the bar occurs in cases of severe eccentric asymmetry because uneven pressure on each side makes the bar slide down toward the depressed side. 3) Backward shift of the bar (hinge-point breaking) occurs when intercostal attachment breaks down because of excessive pressure of the heavy adult chest or uneven pressure of severe asymmetry. Consequently the bar fails to lift the depression to the target level because of posterior movement of the hinge-points.

Since there are different mechanisms of bar displacement, the authors considered that in order to prevent it, strategies for the fixation should be individualized by anticipating the most likely mechanism of displacement. For the symmetric type they considered the standard five-point fixation sufficient. For the eccentric types additional support at the depressed side with a stabilizer was thought necessary in order to block the lateral sliding of the bar. Selection of hinge-points was another point of importance and they liberally used oblique positioning when this seemed indicated. In cases of hinge-point disruption wire reinforcement of the hinge rib should be employed.

The overall result after bar insertion was excellent in 91.3% of the cases. The results in each morphologic type were: The symmetric type had excellent result in 93.5%; the eccentric type in 83.3% of the cases; and the unbalanced type had excellent in 89.4% of the cases. The bar displacement rate (3.4% overall and 1.2% major displacement) compared quite favorably with the bar displacement rates in the literature at that time. While the total complication rate of 18.9% may seemed high, most of the complications were self-limited. In 44 patients out of 322 the bar was removed: In two patients the bar had to be removed earlier while in the other 42 patients the bar was removed after two years as planned. In all these 42 patients, the initial correction was maintained. As a result, this technique based on morphology was considered efficient in terms of stability, simplicity, correction and the ultimate scar.

In 2004, Watanabe *et al* [7] reported a strategy that involved limited use of the lateral stabilizers because they considered that seroma with dermatitis observed on patients who had underwent the MIRPE (**Fig. 19**) resulted from pressure damage caused by the lateral stabilizer that was created to prevent bar displacement. According to authors, this happened because generally children with pectus excavatum are more slender compared with their peers and the patient's physique is never confined within the narrow range of the stabilizers size. The stabilizer often was too large to be placed in the subcutaneous layer of a small or very slender patient with pectus excavatum. The new strategy they proposed to achieve bar stability avoiding seroma and dermatitis is the following:

Technique: The Nuss procedure is performed as first described by Nuss *et al* [19]. A thoracoscope of 3 or 5 mm in diameter is introduced into the right pleural space through a thoracoport placed in the 6 or 7 intercostal space on an anterior auxillary line to observe the right pleural space and anterior mediastinum. Two lateral thoracic incisions are made in the midauxillary line, and a tunnel is created that should allow for placement of the bar at the deepest point of the excavatum deformity, with the bar crossing the sternum in the anterior mediastinum at a 90 degree angle. The bar is fixed to the serratus anterior muscle using about ten nonabsorbable suture on the right side and the same number of absorbable polydioxanone sutures on the left side. The reason why different suture material must be used on the left versus the right is that only the wound on the right will be opened when the bar will be removed, and the nonabsorbable sutures do not have longer durability so as to prevent bar dislocation than absorbable sutures. The stabilizer is used only if the patients are older than 10 years of age and if the bar's stability cannot be confirmed in intraoperative evaluation.

The authors agreed that is absolutely essential to stabilize well the pectus bar intraoperatively before closing to avoid displacement, but the following considerations should be made: 1) A lateral stabilizer is not always necessary to prevent bar displacement in small patients because their ribs and rib cartilage is still soft. 2) Seroma with dermatitis due to pressure damage is a serious complication and very difficult to cure: Risk of infection after spontaneous skin ulceration or perforation, need for use of third generation antibiotics, long hospital stay. Moreover, since the inflammation is caused by the volume effect of the stabilizer, if after resection of a seroma-dermatitis the stabilizer is not removed, infection develops, because the volume effect of the stabilizer on the skin and subcutaneous tissue layer continues and prevents the wound from healing. So, a lateral stabilizer must be removed simultaneously in case of an operation for removal of seroma with dermatitis due to pressure damage. Considering that the above complications occur in young patients operated predominantly for cosmetic reasons, according to authors, the bar should be secured with heavy sutures to the lateral chest wall muscles, and in case that additional stabilization of the bar is necessary, a method such as a wire stabilizer or three-point fixation should be used as a first choice, instead of a lateral stabilizer.

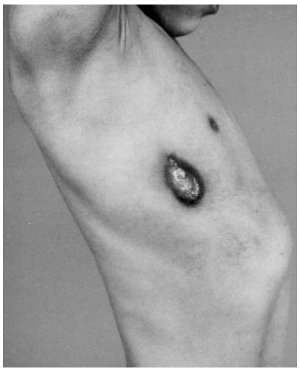
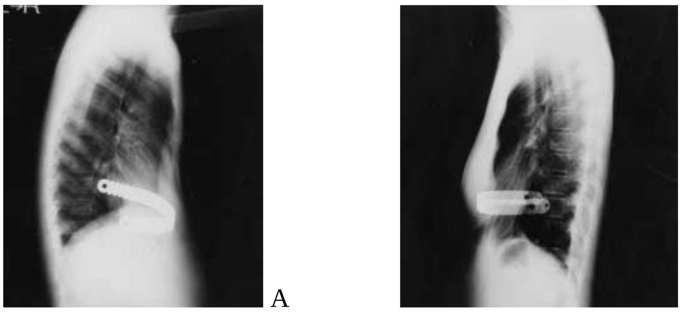


FIGURE 19. Seroma with dermatitis due to pressure damage developing in a 5-year-old boy 2 months after the Nuss procedure, where the stabilizers were placed laterally.

In the authors series, bar displacement rate was 7.5%; 5 patients out of 29 (17%) who had a stabilizer, developed seroma on the side of the stabilizer. Short-term results were excellent in 79.2%.

In 2004, Hisayoshi *et al* [26] reported the development of a titanium alloy plate for pectus excavatum repair in order to improve practical aspects of the presence of the pectus bar in the patient's thorax. The interval from insertion to removal of a bar was at least two years, and the patients might experience diagnostic problems during that period; they could not have an MRI and they need to have a roentgenography instead of an X-ray when it was needed because X-rays could not permeate the steel bar. According to authors, patients operated on with the Nuss procedure were forced to somewhat limit their daily life until the bar was removed to avoid

inconveniences like when the metal detector was set off at the airport. The titanium bar they tested instead, proved capable of elevating the depressed sternum, came out translucently on X-rays **(Fig 20),** allowed MRI because it did not get magnetized, and did not set off the metal detectors at security control points like in airports.
Technique: Basically the procedure is performed as described by Nuss et al. The patient is in the supine position under general anesthesia using a single lumen endotracheal tube. An epidural tube catheter is placed to prevent postoperative pain. A 5 mm diameter thoracoscope is inserted into the right pleural cavity via the right 7th intercostal space on the anterior axillary line. A titanium alloy bar, which was adjusted to the correct length (the outer convex diameter of each patient's chest was measured intraoperatively) was inserted under the sternum through the bilateral pleural cavity. The bar was inserted with the convexity facing posteriorly, and then turned over, thereby correcting the deformity. A lateral stabilizer to prevent bar dislocation was not used in this series and no chest drainage tubes were required. Each patient had strict bed rest for the first 2 days after operation to prevent bar dislocation. Patients were forbidden to participate in athletic events or play contact sports for three months after the operation. Removal of the bar is scheduled three years after the operation.



A B

FIGURE 20. (A) X-ray of a steel bar; (B) X-ray of a titanium alloy bar. Portions of the bar come out translucent on the X-ray.

The technical modifications to the Nuss procedure proposed by Hendrickson *et al* [33] were aiming at the prevention of cardiothoracic and vascular injury, and involved changing patient's arm position and thoracoscopy side, and performing thoracoscopy and dissection through the same incision.
Technique: The patient is positioned on the left edge of the table with the left arm padded over the forehead. A right arm board is routinely used **(Fig. 21).** Bilateral vertical skin incisions are made in the midaxillary line. Left chest thoracoscopy is performed: A 5-mm port is carefully inserted via the superior aspect of the left vertical incision using a Veress needle. A 5-mm 30o scope is introduced in the left hemithorax after pneumothorax is achieved. A second 5-mm port is placed in the inferior aspect of the left vertical incision to accommodate an Endo-kittner, which makes accurate and detailed dissection of the retrosternal area under direct thoracoscopic vision **(Fig. 22).** Once the mediastinal dissection is complete, the Nuss bar introducer is inserted and advanced across the mediastinum under direct visualization. The Nuss bar introducer is inserted through either the right or the left hemithorax. Next, the pectus bar is inserted with the tracheostomy tape and advanced across the mediastinum under direct visualization. A tracheostomy tape is then grasped and pulled across the mediastinum. The pectus bar are tied to one end of the tracheostomy tape and the bar advanced across the mediastinum under direct thoracoscopic visualization. The bar is rotated and thoracoscopic evaluation of the hemithorax and mediastinum assures adequate positioning of the bar and confirms no injury to vital structures. Then, the bar is anchored into position with bilateral stabilizers which are secured with either nonabsorbable suture or wire depending upon attending preference. After the pectus bar has been rotated and anchored into position with bilateral stabilizers, a final inspection of the mediastinum and left chest is performed. A post-procedure chest radiograph is obtained before extubation.

FIGURE 21

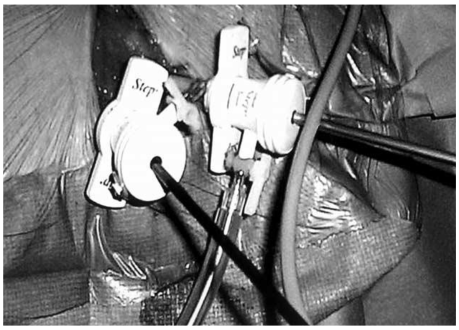


FIGURE 22

There have been no intraoperative or postoperative bleeding complications; Blood loss was less than 5 mL in all cases of the authors' series.

The benefits of this method are: 1) Left thoracoscopy ensures that the heart is under direct visualization during the entire procedure especially during dissection and bar placement. Thus, heart injury may be avoided. Although the chest wall deformity shifts the heart toward the left, careful insertion of a 5-mm, 30o scope is safe because of the patient's position: Having the left arm away from the lateral chest wall permits an adequate area for camera movement. When the thoracoscope is inserted this way, the heart that is usually the first structure identified, can be kept in the operative field at all times 2) The use of the Endo-kittner dissector permits accurate and detailed mediastinal dissection. 3) A vertical rather than a horizontal skin incision in the midaxillary line on each side improves cosmesis. 4) Other methods developed earlier to ensure safe substernal dissection such as using a subxiphoid incision are unnecessary.

Schaarschmidt *et al* [36] feeling that pneumothorax, pleural effusion, and pericarditis were associated to mechanical irritation by the parasternally intrapleural bar position, and noting significant adhesions of the lungs to the bar in redo procedures, devised a technique of placing the bar or bars into an entirely extrapleural position by bilateral thoracoscopy.
Technique: A 5-mm trocar is introduced into the lower third of the thorax bilaterally at the midaxillary line and at least 2 intercostal spaces caudally to the skin incision. No additional incision is used; just the standard exit holes of the bilateral submuscular suction drainages are taken as port accesses. Then, the thorax is inflated by low-pressure carbon dioxide, and a nonpointed forceps is introduced through the marked right intercostals space under thoracoscopic vision until the tip of the forceps is visible below the pleural layer. Beginning at this point, a small extrapleural pouch is dissected similarly as in thoracoscopic pleurectomy. Next, the clamp is advanced without piercing the pleura first along the intercostal space, and a wide extrapleural pouch is gradually dilated

and extended toward the pleuropericardial fold, taking care to stay on the pleural side of the internal mammary vessels, that is, to have them not between dissector and pleura. Then, the forceps is replaced by the Lorenz dissector (Walter Lorenz Surgical, Jacksonville, Fla), which gradually lifts the pericardium from the sternum under indirect vision through the intact mediastinal pleura. Then, the right-sided dissector is held by an assistant, and a corresponding extrapleural tunnel is developed likewise from the left side. Under thoracoscopic vision, the tip of the Lorenz dissector coming from the right becomes visible under the left mediastinal pleura and the left-sided forceps is advanced extrapleurally until the tips of the 2 instruments crosse. Then, the left-sided forceps is gradually withdrawn while the dissector followes it through the leftsided extrapleural tunnel, maintaining continuous contact between both instruments until the dissector emerges at the left intercostal entry poin **(Fig. 23).** If several bars are introduced through the same skin incision, this procedure is repeated for each individual bar at several intercostals spaces, taking care to make the extrapleural pouch wide enough to allow for turning of all the bars. The bar is secured to the stabilizer by 10 to 14 pericostal braided polydioxanone sutures under thoracoscopic vision, keeping the lungs well out of the way by the residual pneumothorax. On both sides, the extrapleural bar position is controlled by a second final-look thoracoscopy.

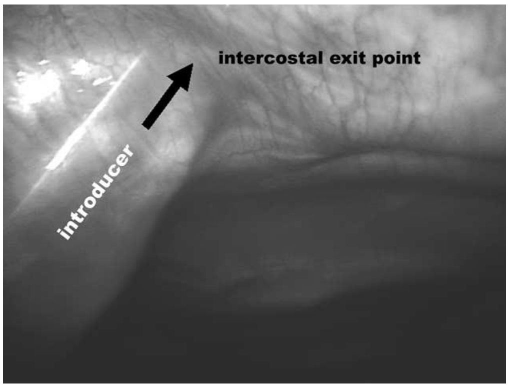


FIGURE 23 Thoracoscopic view of the left hemithorax: The bar introducer has already been passed entirely through both extrapleural tunnels and is seen to leave the thorax through the leftsided intercostal exit point (black arrow) lying in an entirely extrapleural position.

This extrapleural Nuss procedure was feasible in 92% of the authors'patients (the early 8% of the cases where minor pinpoint holes of the pleura were visible now and then, were associated to the learning curve). There was no secondary pneumothorax, no case of late seroma, and no case of pericarditis. Long-term result analysis after removal of the bar showed excellent results in 88%.

The benefits of this technique are:1) Significant adhesions of the lungs to the bar, and trapping of lower lobes may be discovered during redo with the transpleural bar. With an extrapleural bar, less or even no adhesions of the lung may be expected which would facilitate redo surgery. 2) With the transpleural procedure, the pericardium is somewhat fixed and approximated to the sternum by the mediastinal pleura at the bar entry points into the retrosternal space. Conversely, because of the wide mobilization of pericardium and ventral parietal pleura for passage of extrapleural bars, in the extrapleural technique, the pericardium is allowed to fall further back from the sternum, which increases the sternopericardial distance. 3) Patients have less pain because the bars no longer cross the pleural barrier and do not irritate the entrance and exit holes.

However, according to Dr. Nuss [24] this extra-pleural approach is technically more difficult and the internal mammary vessels are at increased risk.

Since the Nuss procedure was presented, elevation of the chest during surgery was done only by the introducer. When the Vacuum chest wall lifter was developed, it was also proposed as a non surgical method to elevate the chest during the Nuss procedure in addition to the introducer **(Fig. 24)** [35].

FIGURE 24 Use of the vacuum cup during the Nuss procedure.

In 2006 JRM de Campos *et al* [8] also proposed a new technical approach of the MIRPE in which patient’s arms position s and the point of insertion of the optical trocar were different from the original procedure.

Technique: The patient lies in the supine position on a 12 cm-high cushion that extends from the head to the waist and is placed longitudinally on the surgical table, parallel to the median line. The patient's arms are not abducted (**Fig 26**) but are stretched along the body and fixed to the surgical table (**Fig 25**). The procedure is performed under general anesthesia and orotracheal intubation. The optical trocar (5 mm and 30º) is inserted 2 intercostal spaces cranially (above) with respect to the space where the metal bar will be introduced at the median axillary line. Otherwise, the operative technique remains as originally described by Nuss.

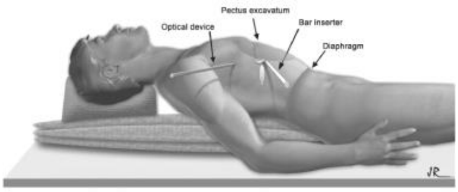


FIGURE 25

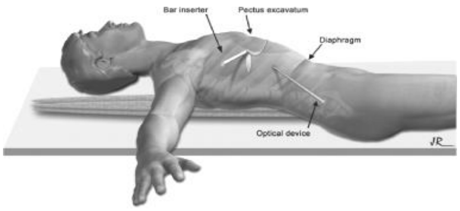


FIGURE 26

The benefits of this new approach are:

1. Increased safety regarding the introduction of the trocar; this is because this procedure is carried out at a higher level in the pleural cavity, thus reducing the risk of a diaphragmatic lesion.
2. Easier handling of the optical device; this enables better visualization of the bar inserter during dissection of the anterior mediastinum.
3. Optimization of the resources offered by the 30º optical device, with better visualization due to the possibility of complete rotation; this enables working laterally or under the bar inserter.
4. Better visibility of the pleural cavity, of the sites to be handled, and of the dissected tunnel near the posterior wall of the sternum; thus, the pectus excavatum deformity does not obstruct optical image.
5. Easier identification of the intrathoracic vessels, such as the internal thoracic arteries, and a better view of the left pleural cavity in cases in which this cavity is open.
6. Easier passing of the fixation wires of the metal bar in the right hemithorax to avoid its displacement.
7. Better positioning of a thoracic drain, if necessary in case of aerial fistulae, using the trocar orifice; this position is closer to the apex of the thoracic cavity.
8. An aesthetically more acceptable result; the small scar approximately 5 mm that is covered by the patient's arms due to its location closer to the axillary cavity.
9. Last, but not least, minimization of the possibility of a brachial plexus lesion; this is due to the placement of the arms of the patient along his/her body.

The method proposed by Furukawa *et al* [34] has similar principles with the Hendrickson *et al* method but involves different instrumentation. More specifically:

Technique: The patient is intubated with a single-lumen endotracheal tube. Bilateral, coronal, 3-cm skin incisions are made in the anterior axillary line, and a thoracoscope 4 mm in diameter with a 0o or 30o scope is carefully inserted through the left skin incision. No special instruments such as gasketed trocars, valved ports, or insufflation tubing are necessary. Then, the Nuss bar introducer is also inserted through the left chest and used for blunt dissection across the mediastinum under direct thoracoscopic control. The chest wall is retracted upwards, the retractor being inserted into the thoracic space from the same skin incision. The introducer and the scope are introduced in the same plane and almost parallel through the same skin incision **(Fig. 27)**. The narrow instrumentation angle allows optimal visualisation of the dissection through the mediastinum. When the introducer tip is advanced through the mediastinum, the scope is advanced simultaneously over the introducer, so that the introducer tip is always located in the centre of vision. In mild cases, the introducer tip is continuously under visualisation from the left to the right incision. In severe cases, in which the depression prevents continuous visualisation to the right side, the dissection is made until the introducer tip reaches the lowest point under the sternum. The scope is then re-inserted from the right side. The tip can immediately be visualized and the introducer can be advanced. The switching of the scope from the left to the right side takes little time, because the scope is inserted through the same incision as the pectus bar, and no ports or additional incisions are required. Once the introducer has been penetrated through the mediastinum, and the tip guided out of the cutaneous incision on the opposite side, a tracheostomy tape is used to tie and attach the introducer tip firmly to the pectus bar. The introducer and the bar are then pulled across the mediastinum. After the bar has been rotated, it is anchored into position with non-absorbable sutures. The mediastinum and both the right and left thoracic cavities are then inspected by the scope. At the end, a chest x-ray is taken before extubation.

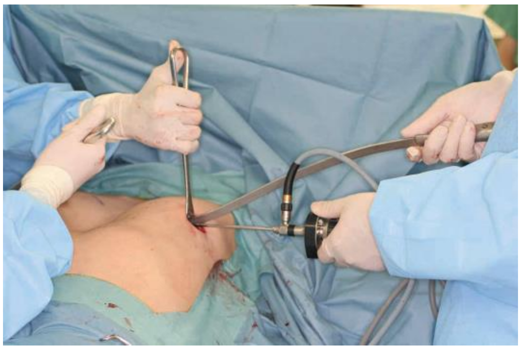


FIGURE 27 The introducer and the thoracoscope are inserted through the same ski incision on the left side

There were no intraoperative bleeding complications. Blood loss during all operations was less than 10 ml. In one case there was intrathoracic bleeding a month postoperatively that required needle thoracocentesis.

The rationale of this development was: Cardiac injury has been attributed to the ‘‘blind’’ passage of tunneling devices into the anterior mediastinum when the surgeon does not manage to keep the tip of the introducer under direct vision the moment it penetrates the mediastinum to reach the opposite thoracic space. This technique, instead, keeps the introducer tip under continuous direct vision by thoracoscopy; changing the scope from the left to the right side in severe cases takes little time. Other benefits of this procedure are: The skin incisions are few and small, no special devices such as gasketed trocars, valved ports, or insufflations tubing for carbon dioxide are needed, substernal dissections such as through a subxiphoid incision are unnecessary, rotation of the pectus bar is always under direct vision.
However, authors identified as demerit of their technique, the difficult handling of the introducer and thoracoscope because the range of movement of both instruments is restricted by the narrow angle that arises after their insertion through a single incision. They consider that retraction of the skin by an assistant and increasing experience of the surgeon helps to ease this difficulty.

In 2008 Park *et al* [59] reported a "specific displacement mechanism-based bar fixation method" that involved:
1) The multipoint fixation technique (MPF): It is a multipoint fixation to the corresponding ribs by means of pericostal sutures (wire or absorbable) at the end of the bar plus hinge point(s) (end-hole fixation + hinge point fixation) as a fixation of choice. For pericostal suture bar fixation, it is often difficult to access the target ribs to be sutured via the skin incision. Therefore, all the necessary pericostal sutures are carried out with a specially designed method, the ''through-the-skin suture technique'': To keep the incision small, just the size for pectus bar insertion, the entire suturing process is performed outside the lateral skin incisions. First, the targeted rib is palpated and the needle stick is made directly through the overlying skin, passed around the rib, and passed back through the skin. Then, the sutured wires are grabbed via a subcutaneous dissection and pulled out through the incision. The retrieved sutures are passed through the end-hole of the bar and tied. The hinge point fixation suture is also made with the same technique. This technique makes pericostal suturing easy even to the remote ribs from the incision, while the skin incision remains small (1 cm each side). [59],[29]. The MPF is protects against type 1 displacement mechanism (see mechanisms of bar displacement according to Park *et al* page 20).
2) The Crane technique: In adults and in severe depressions, the passage of the introducer under the sternum was particularly difficult carrying the risk of heart injury and the traditional hinge system involving intercostal muscle bundle was not strong enough to elevate and sustain the heavy or severely depressed chest. In an effort to eliminate these difficulties, Park and his co-workers invented the Crane technique: The patient is placed in a supine position, and both arms are freely hung on overhead slings to avoid arm stretch. A pectus bar shaping is performed on the operating table by the surgeon, which makes it custom-fit to the patient's chest wall morphology. One-centimeter skin incisions are made on both mid-axillary lines. At this point, in adults, teenagers or patients with severe chest depression, the "Crane technique" is applied: Wire suturing to the bone of the xiphi-lower sternal area and/or the lateral side of the sternal body, and lifting the wire suture along with the sternum by an operating table-mounted retractor system (**Fig 28** [29]). This way, the sternum is elevated, so that the passage of the introducer through the mediastinum followed by a guide (20F chest tube) and the bent bar, and the rotation of the bar is made more safely. By rotating the pectus bar, the convexity of the bar lifts the depressed chest wall. Both ends of the pectus bar and hinge points are fixed to the adjacent ribs with pericostal sutures. Hemo-vac catheters are inserted in the subcutaneous pockets around the pectus bar or in the pleural cavities.

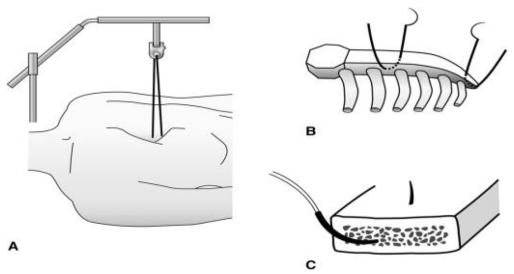


FIGURE 28 Crane technique: Elevation of the depressed sternum before mediastinal passage of the introducer and pectus bar.
A, An operating table mount crane system (a crank system) elevates the sternum via a wire suture passing through the patient's sternum.
B, Wire suture(s) is (are) delivered through the sternum at the xiphoid process or the lateral side of the sternal body.
C, Suture needle strictly passes through the bone between the outer and inner tables of the sternum.

The Crane technique offers two main effects: 1) It alleviates the pressure on the bar and hinge points encountered when treating adults (as opposed to children) because of their relatively heavy and stiff chests. The hinge system involving intercostal muscle bundle is not strong enough to sustain the bar for heavy chests. The Crane technique prevents tearing of the intercostal muscles at the hinge points that could result in bar displacement. It prevents type 3 displacement mechanism (see mechanisms of bar displacement according to Park *et al* page 18). 2) It elevates the chest wall allowing safe passage of the introducer and rotation of the bar without risk of heart injury.

The bar displacement rate was decreased with this mechanism-based approach (1.8%). In addition, the major complication rate was decreased in 2.0% after MPF and the reoperation rate dropped to 1.6% with the MPF.

In 2008 Pilegaard *et al* [30] proposed a modification to the Nuss technique that involved using a shorter bar and placing one stabilizer on the left side of the bar as close as possible to the entry of the thoracic cavity, in order to make the bar stable and avoid skin wood.

The rationale for their modification was the following: If the stabilizer is placed closer to the entrance of the bar into the thoracic cavity, the risk of bar rotation is decreased because the point where the stabilizer is attached will function as a hinge in case the bar is displaced. The closer this point is to the centre of the pectus bar, the less likely it is that it will rotate. It is also possible that this generally decreases the movement of the pectus bar in the tunnel created in the anterior part of the thoracic cavity causing less inflammation and reduced problems with seroma. The medial positioning of the stabilizer is possible when it is used for a short bar (d).
Technique: The patient is placed on in the supine position with abduction of both arms under double-lumen intubated anaesthesia. A 5-mm blunt-tip trocar is introduced into the thorax for the use of a 30o videothoracoscope to define the deepest point under the funnel chest. A template has been formed with a similar shape as the anterior thoracic wall and a pectus bar (Lorenz Surgical, Inc., Jacksonville, Florida, USA) has been bent to match the template. The pectus bar is 5 cm shorter than the one originally described by Dr. Nuss. If the patient presents with asymmetric pectus excavatum, the metal bar is bent asymmetrically according to the method described by Park *et al*. A subcutaneous tunnel is created by blunt dissection to the highest point of the funnel (thoracic entry and exit points). An introducer is inserted into the thorax and pushed between the sternum anterior to the pericardium. A 0-ethibond suture is tied to the eyelet at the end of the introducer which is then pulled back guiding the suture through the thoracic cavity. The pectus bar is attached to the suture and pulled through the tunnel with the convex side facing down. Finally, the bar is rotated 180o and the sternum is tilted upward. A stabilizer is placed on the left side of the bar as close as possible to the entry into the thoracic cavity to avoid rotation (the more medial positioning of the stabilizer is facilitated by the shortness of the bar). In addition, the pectus bar is secured on the right side by two or three 0-polydioxane (PDS) sutures around the ribs. If an acceptable cosmetic result cannot be achieved with a single pectus bar, an additional bar is introduced.
The theoretical considerations that led to the above modifications had some importance because the incidence of bar displacement or rotation was <2% and seromas occurred in <3% of our patients.

In 2008, Torre *et al* [28] after testing the absorbable LactoSorb stabilizer on a group of 86 patients, suggested the routine use of an absorbable stabilizer **(Fig. 29)** in pectus surgery. According to authors, such stabilizer is safe, effective in stabilizing the bar in pectus surgery, less traumatic; thus causes less discomfort and makes the bar removal easier.

The rationale for employing an absorbable stabilizer was the following: 1) It is made of poly-L-Lactic and polyglycolic acid which is a material used for many years in other kinds of surgery and has been proven to be safe. 2) Bar displacement is one of the most serious complications of the Nuss procedure that most surgeons try to prevent in several ways but with the help of metallic stabilizers always; However, at the time of the bar removal that the metallic stabilizer has to be dissected and detached from the bar, the dissection and detachment of the metallic stabilizer often covered by scar tissue or bone can be quite difficult; in cases of a bilateral stabilizer, two incisions have to be made and the above procedure must be made not on one but on both sides.

Technique: Long-term absorbable stabilizers have become available (LactoSorb, Biomet, Jacksonville, FL, USA). The LactoSorb stabilizer has the same shape and size as the metallic one, it has the same holes and is transparent. The MIRPE according to Nuss is performed with the exception that absorbable stabilizers instead of metallic ones are used. The LactoSorb stabilizer is secured with a polyglycolic suture and other absorbable stitches are passed through the holes of the stabilizer fixing it to the pectoral muscles. The maneuver is easier because the surgeon is able to see the needle through the transparent stabilizer. One bar with one LactoSorb stabilizer is usually placed; two bars and two LactoSorb stabilizers may also be used.

The LactoSorb stabilizer was palpable under the skin for at least 6-9 months, and after progressively changing its shape and becoming slightly mobile, it was not palpable any longer at 9-12 months. This material had been previously used for a long time in humans without adverse effects. Therefore the only concern could regard the efficacy as “pectus bar stabilizer” of a device which loses its strength and disappears within a few months. In not any of the authors’ patients who received the absorbable stabilizer, did bar displacement occur. The efficacy of LactoSorb in stabilizing the bar over a long period even after its complete absorption could be explained by the formation of adhesions and calcifications around the bar. No infection was observed. In three cases swellings at the site of the LactoSorb 6, 8 and 9 months after the operation were observed. An attempt to drain the subcutaneous collections was made and from one patient no liquid was collected while from the other two collections few ml of fluid with negative culture were obtained. In all cases the absorption was complete after a few days. Those 3 subcutaneous collections were not clinically particularly relevant and they might be due to the dissolution and substitution of the LactoSorb material during the absorption process. Therefore, they were considered more as part of this process than a true complication.

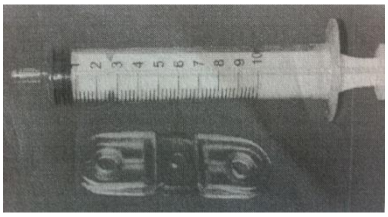


FIGURE 29. LactoSorb stabilizer

However, a year later, Pilegaard *et al* [18] evaluating the results obtained from the use of absorbable stabilizers in their pectus surgeries (they performed the Nuss procedure as described in their 2008 report using a pectus bar 5-8cm shorter and absorbable stabilizers instead of metallic ones) questioned their routine use, as it seemed that absorbable stabilizers were associated to significantly higher incidence of complications: They broke easier (3.5% of the Lactosorb stabilizers broke within 6 weeks from surgery) and did not fixate the bar laterally as well as metallic stabilizers (3.5% dislocated laterally within 8 weeks from surgery); thus an increased risk of failure was identified. They said, however, that this was not unlikely a consequence of the high stress forces on the stabilizer that are more pronounced when a shorter pectus bar is used , which in all their patients was used, and of the higher stress on the ribs of adult patients, who were the majority of their failed surgeries. It remains to be determined if the incidence of failure is reduced using a longer pectus bar.

In 2009 JRM de Campos and his co-workers published a study [16] that described the following modifications to the Nuss technique:

1) New stabilizer model: It has central grooves in the posterior surface, which allow better sliding over the bar, regardless of the bar's curvature **(Fig. 30).**

2) Placement of two stabilizers in a more medial position to achieve bar stability without pericostal stitches or causing skin wound: In the original technique, two stabilizers were placed laterally at the bar edges. In this technique, the two stabilizers are placed in a more medial position (a) close to the entry and exit of the bar in the intercostal space, posterior to the muscles. Additional pericostal stitches are not needed for these stabilizers. The more medial position of the stabilizers is possible because their new shape enables them to slide along the bar regardless of its curvature **(Fig 30).** The stabilizers are not placed close to cartilage. However, the authors considered the medial position of the stabilizers inconvenient, because it requires additional dissection of the pectoralis major muscles medially to allow the stabilizers to be placed posterior to them.

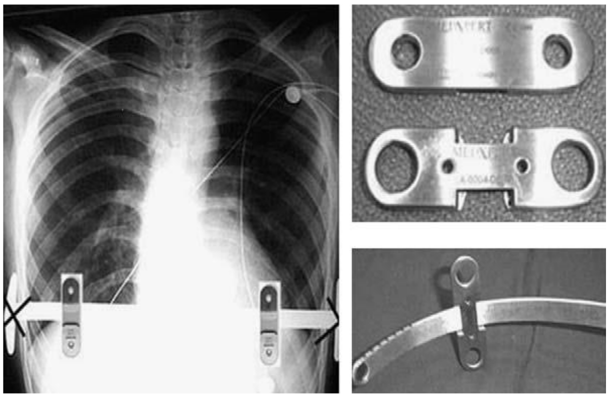


FIGURE 30

3) Protection of the serrated edge of the bar during its removal: The bar is removed from the side on which the stabilizer was fixed after its maximum bilateral alignment. The protective plastic film (rubber protectors) **(Fig. 31)** around the distal extremity of the bar protects the surrounding tissues against the bar's sharp edge when it passes along the fibrous tunnel, and thus avoids bleeding. This very thin film does not increase the thickness of the bar. Additionally, it is closely bound with double wires to avoid the risk of being retained within the tunnel.

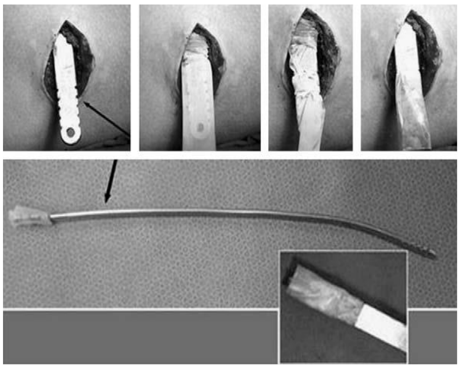


FIGURE 31

No complications were observed.

In 2011 Miguel Lia Tedde *et al* [9] proposed a combination of the technique of De Campos *et al* end the technique of Pilegaard *et al*. Use of a shorter pectus bar that is fixated by medially positioned stabilizers. The authors considered a shorter bar more stable; one stabilizer at each side of the bar distributes the forces to at least two ribs providing a stable basis for the correction without risk of displacement; the medial position of the stabilizer protects from skin wood and dispenses with pericostal sutures and wire stitching (according to authors, patients who received the "third point fixation technique had thoracic pain and discomfort close to the fixation points, perhaps due to compression of the intercostal bundle; in the five point fixation technique, rupture of the wire sutures used to secure the stabilizer and/or bar on the underlying rib was a common complication. Furthermore, the broken wire could hamper removal of the bar by obliging the surgeon to find and extract minute wire pieces. As a result, residual wire fragments remain embedded under the ribs of some patients). Not any of the 51 patients who received this technique, did have any complication.

The incidence of intraoperative cardiac perforation was unclear, but numerous case reports demonstrated that it continued to occur despite thoracoscopy, blunt left chest dissection and the chest elevation techniques. Johnson *et al* [3] considering unacceptable the risk of a complication such as the cardiac perforation in a surgery predominantly performed for cosmetic reasons, tested a novel sternal lift system for the Nuss procedure. Technique: Preoperatively, each patient's anatomy is marked: The intercostal spaces, anterior axillary and midaxillary lines, xyphoid, sternum, inframammary crease, deepest point, and incision sites. A 5-mm scope halfway between the anterior axillary and midaxillary lines is placed. A small (3-cm) subxiphoid incision is then made. After removal of the xiphoid, digital dissection creates a plane between the pericardium and posterior sternum, permitting the insertion of a tonsil sponge on the end of a sponge stick to finish separating the pericardium from the posterior sternum. The lift **(Fig 32)** is inserted, and the index and middle fingers are used as a track to guide it securely beneath the sternum and to further eliminate inadvertent substernal damage. The sternum is elevated manually with the lift to accurately gauge the applied force on the sternum **(Fig 33A)**. The lift screws into the stabilizer to complete the sternal lift system **(Fig 33B)**, holding the sternum in place and increasing the distance between the pericardium and sternum, which improves visibility **(Fig 34)**. This lift attaches to any standard body retractor. Bilateral 2.5-cm incisions from the anterior axillary to the midaxillary lines are made. A cryostat creates a tunnel through these incisions into the thoracic cavity. An introducer with umbilical tape is inserted. This crosses the thoracic cavity easily because of the preplaced sternal lift system. For adults, typically a second introducer with umbilical tape is placed inferiorly. The lift is removed once the introducers are placed. One at a time, each introducer is removed, replaced with a pectus bar, and stabilized with No. 2 steel wire. Each bar is further secured to the ribs by use of two endoclosure auto sutures (No. 1-PDS, fish hook) on each side. The muscle is closed to the stabilizer with 0 Vicryl. The wound is closed with braided polyblend sutures. The previously made subxiphoid incision is used to insert two small chest tubes, one in each pleural space.

FIGURE 32

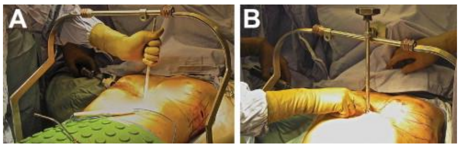


FIGURE 33

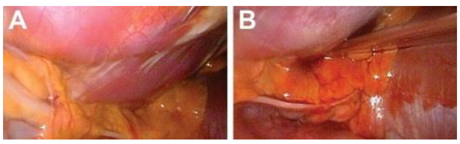


FIGURE 34

No complications were seen in the authors series. This sternal lift system improves the visual field and increases the space between the posterior sternum and the pericardium, minimizing the risk of cardiac perforation. It is safe because it is guided into position with the index and middle fingers, completely separated from the pericardium. It supports the sternum from xiphoid to manubrium so as to maximize stability. According to authors, this approach is feasible even in patients with severe pectus excavatum (ie, Haller index >7) and should strongly be considered, especially in patients with a severely elevated Haller index.

The authors acknowledged that this approach necessitates an additional incision and scar on the anterior chest wall which is undesirable in a cosmetic procedure, but they considered it justified, because it eliminates a chest tube incision which is a standard protocol, and because the additional incision is small with little to no skin stretching that heals very well.

Yong Jeong *et al* [4] with their 2014 article, practically proposed a method of elevation of the chest based on the Crane method and the Johnson method, but with a difference: Use of a needlescope and mini-endo scissors **(Fig. 35).** Technique: The Crane technique is employed to elevate the depressed sternum as previously discribed, but in order to ensure a surgical field a 2-mm needlescope and mini-endo scissors are applied along the mid-axillary line (instead of a 5-mm scope inserted through an additional skin incision as proposed by Johnson *et al*).

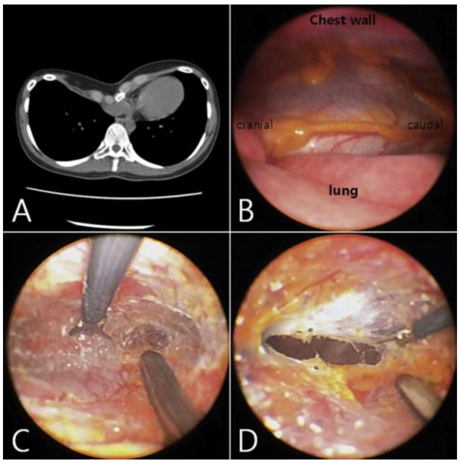


FIGURE 35. (A) Chest computed tomography showed severely depressed anterior chest wall resulting in dimensional and location changes of heart. (B) Applying Crane technique, (C) needlescope demonstrated the pectus clamp and endo scissors approaching the substernal area and (D) reaching the opposite pleura.

This method elevates the sternum with direct inspection of the surgical field and meticulous dissection of the substernal space without additional skin incisions. In the authors series there was no intraoperative cardiac bleeding. However, one case presented delayed-onset hypovolemic shock during the postoperative recovery period. The cause of pin-point injury on the right ventricle in this case was not clear. Although it may have been caused by the deep sternal wiring used in the Crane technique, the wire had not observed under the sternum during the needlescope-assisted substernal dissection and bar insertion.

Another method for elevation of the chest during the Nuss procedure, was presented by Daabin Kim *et al* [2].

Technique: The patient is positioned supine. The arms are placed in adducted position next to the chest. To have access to the lateral chest, several folds of blankets are placed under the patient's back to elevate the chest, allowing the arms to be in the lower position on the operating table. Having the arms adducted also facilitates the attachment of the Thompson rail clamp or Rultract Skyhook System since the arm rests are not needed. Furthermore, with the arms in adducted position, the concern for brachial plexus nerve injury is mitigated. Bilateral lateral transverse chest incisions are made for the insertion of the sternal bar. Through the right lateral chest incision, a 5-mm port is inserted directly through the wound into the chest cavity. On the left side of the chest, to facilitate anterior mediastinal dissection, a 5-mm incision is made slightly superior to the left chest incision, and a 5-mm port is inserted. Carbon dioxide insufflation at 5 mm Hg pressure is used to suppress the lung to create an operative space. The anterior chest is marked with a surgical marker to approximate the desired position of the sternal bar. A 25G needle is used to probe the chest for proper position where the T-fastener suture will be applied. A typical position is approximately 1 cm superior to the transverse lie of the sternal bar lateral to the sternum. With the thoracoscope, the needle is monitored as it enters the chest lateral to the sternum. Once the proper position is determined, a 16G angiocatheter is inserted. The needle within the angiocatheter is removed leaving the angiocatheter in place. Through the angiocatheter, a size 5 Fiberwire suture (Arthrex, Naples, FL) is passed into the thorax. A Maryland grasper or tonsil clamp is then directly placed into the lateral chest wound (not through the port) to retrieve the Fiberwire suture through the lateral chest incisions (**Fig 36**). The suture is then tied to a metal plate with three holes (3.5 mm wide-angle, low-profile reconstruction plate 3 holes; Synthes Corp, Monument, CO). An umbilical tape is tied to the outer hole of the metal plate, which will be used to remove the plate later (**Fig 37**). The metal plate is pulled through the rib space into the chest cavity and observed to lie against the underside of the anterior chest wall. The same maneuver is done on the contralateral side to create two T-fastener sutures that are used to elevate the anterior chest from both sides of the sternum. The sutures are attached to a Thompson retractor crossbar or Rultract Skyhook crossbar. Once the sutures are tied to the crank system, the anterior chest is elevated to the desired height so that the chest concavity is effaced (**Fig 38**). A grasper placed through the lateral chest incision is used to grab the Fiberwire suture that has been placed through a 16G angiocatheter. After the Fiberwire suture is delivered outside the lateral chest, it is tied to a metal plate with three holes. Umbilical tape is tied to the outer hole of the metal plate for later removal of the plate.

The Fiberwire sutures are tied to a crank that is attached to a crossbar. The anterior chest is elevated to the desired height by using the crank. With the anterior chest elevated with the T-fastener crank system, two laparoscopic peanut dissectors are passed into the left lateral chest incision through the open incision. While under thoracoscopic observation, the two peanut dissectors are used to bluntly dissect the anterior mediastinum to create a tunnel from the left to the right chest cavity (**Fig 39**). The dissection is very simple and needs only a gentle downward and lateral sweeping movement to clear the areolar tissues between the sternum and the pericardium. At the end of the dissection, the thoracoscope will easily pass through the anterior mediastinum to visualize the contralateral chest cavity (**Fig 40**). Once the anterior chest has been elevated, an endoscopic peanut dissector is used to bluntly dissect the anterior mediastinum from the left to right chest. The sternal bar is shown lying below the sternum. After the sternal dissection, there is a wide passage through which the introducer and the sternal bar may pass through.

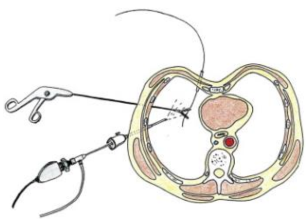


FIGURE 36

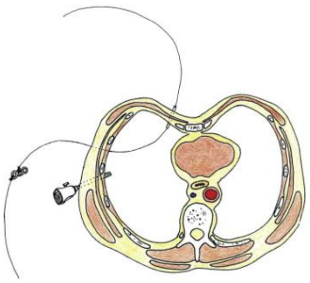


FIGURE 37

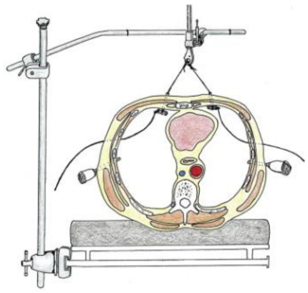


FIGURE 38

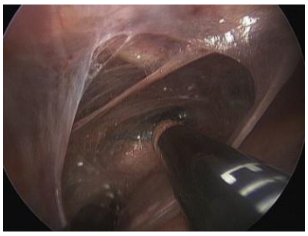


FIGURE 39

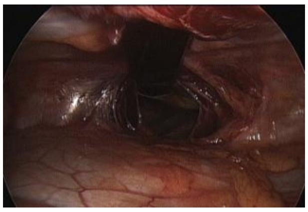


FIGURE 40

According to authors, the advantages of the T-fastener method are threefold: First, it requires no specialized equipment. The metal plate and the Fiberwire suture can be found in most operating rooms that provide orthopedic surgical service. Second, no incision need to be made on the anterior chest (needed for the Johnson modification). The needle hole created by the placement of the 16G needle requires no suture closure. In fact, it does not require any dressing. Third, it is a secure system that does not cause any fracture or tear to the anterior chest structure (the Park method occasionally causes sternal fracture). The strength of the system is such that the patient can be elevated off the operating table.

The authors recognized one disadvantage to the T-fastener suture technique: After the introducer has traversed the mediastinum under vision and the sternal bar has been positioned, removal of the metal plate is necessary. To retrieve the metal plate, the previously placed umbilical tape that has been tied to the end hole of the metal plate is pulled. Occasionally, the umbilical tape will lie underneath the sternal bar, preventing the metal plate from coming out. In this situation, a grasper is inserted through the lateral incision to grab the metal plate directly to pull it out. It has been observed that once the sunken chest has been elevated, the anterior mediastinum can be bluntly dissected without difficulty. Using endoscopic peanut dissectors, the areolar tissues between the sternum and the heart is gently pushed away. This maneuver is done entirely under thoracoscopic vision. It is possible at the end of the dissection to pass the thoracoscope through the anterior passage into the contralateral chest without any hindrance. Passing of the introducer is also done under thoracoscopic vision; thus, the safety of the heart during this move is assured.

Jinbo Zhao and his colleagues [5] explored intraoperative ultrasonographic visualization during the introducer's passage as a means to prevent heart injury during the Nuss procedure.

Technique: A water-filled balloon (WB) is placed in the sternal depression to fill the gap between the ultrasonic probe (UP) and the chest wall (**Fig 41)** facilitating ultrasound visualization. Ultrasonography can measure the distance between the inner table of the sternum and the pericardium, it monitors the creation of an extrapleural tunnel bilaterally, and guides the dissector tip, placed laterally to the sternum, during its passage through the deepest depression of the sternum between the sternum and pericardium to the opposite side, protecting the heart from injury (**Fig 42).**

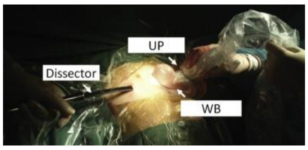


FIGURE 41

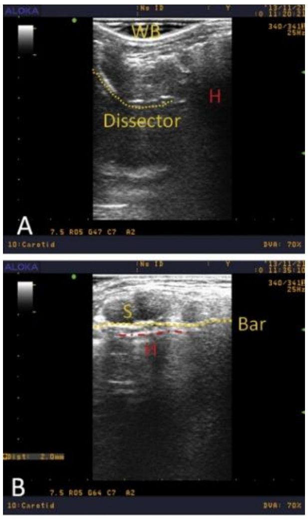


FIGURE 42

This extrapleural Nuss procedure has certain advantages: First, the whole surgical procedure can be directly monitored by ultrasonography, which may reduce the potential injury to the pericardium and to the heart. Second, this technique can be used in patients who have an obliterated pleural cavity, where thoracoscopy could be hazardous. There has been no blood loss or pneumothorax. Compared with our previous technique, this procedure is slightly longer.

That a short bar is more stable than a large one was just a hypothesis, until the first report on the effects of bar length on the incidence of bar dislocation came by Messineo *et al* [17].

The authors first created a mathematical model (using computer-assisted mechanical simulation) to define mechanical stresses acting on pectus bars of different lengths: The contact of the bar with the ribs prevents bar movements in the saggital plane. The sternum exerts a force on the upper part of the bar (F) that generates a torque (t) which induces rotation of the bar around its axis (flipping). The sutures-stabilizer generate a reactive torque (tR) that balances (t) and does not permit the bar to rotate on its axis. When t>tr the bar flipps. It is known that the torque (t) acting on the extremities of a bar is the vectorial product between force (F) and its arm (r) [(t=Fxr)]. Longer bars are more curved and thus have longer arms, and they are secured with stabilizers placed more laterally, while shorter bars have shorter arms and are secured by stabilizers placed more medially. In accordance to the above elements, smaller torque acts on the complex bar extrimities-sutures/stabilizer of a shorter bar. In fact, the mathematical model demonstrated high stress peaks around the stabilizer areas in the long bar, while lower stress values were found on the same region in the short bar (**Fig 43).**

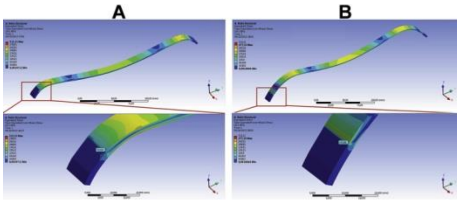


FIGURE 43. Results of the model simulations performed on a (a) short bar and on a (B) long bar.

After the mathematical model practically demonstrated that shorter bar are expected to be more stable than larger ones, the authors decided to apply the Nuss procedure using metal bars three inches shorter than the distance between the mid-axillary lines (the standard Nuss procedure used bars half an inch shorter than the distance between themed-axillary lines)

Technique: When the patient is positioned at the operating table, the most depressed area of the sternal plate and determined points on both sides of the chest ridge of the patient are identified. A 5-mm thoracoscope is inserted 2 intercostal spaces above the right incision site to verify the deepest point of sternal depression and to monitor the procedure. Two curved skin incisions of 3 to 4 cm in length are made at the mid-axillary lines on both sides, and a subcutaneous tunnel is created up to the determined points on the chest ridge. An introducer is inserted into the thorax at the determined point of the right chest ridge to dissect the plane separating the sternum from the pericardium; the introducer is exteriorized on the left side and pushed through the skin incision. A tie is tightly attached to both the introducer tip and the bar and the introducer is pulled backward, allowing the passage of the bar through the dissected plane. The bar is inserted with the concave side anterior and then it is rotated 180 degrees around its axis, thus pushing up the sternum. Stabilizers are routinely inserted on both sides of the bar, as close as possible to the bar end. These are secured with pins and are eventually fixed to intercostal muscles by interrupted polyglactin sutures. An additional bar is introduced if the cosmetic result is not acceptable with a single Nuss bar, and a single stabilizer per bar is placed on opposite sides in this case. If pectus excavatum is asymmetrical, the bar is curved asymmetrically according to the method described by Paark. The results obtained confirmed the expectations based on the mathematical model: A shorter may reduce the risk of bar dislocation.

In 2007 Rushing *et al* presented a study that suggested preoperative allergy testing in selected patients with a personal or family history of metal allergy, eczema, or atopic history [60].

Seven years later, a new report [22] suggested that a preoperative broad allergy metal test should be made routinely to all patients so that a titanium bar is used when there are indications of allergy; positive personal or family history of allergic reactions or positive allergy tests.

The rationale for that suggestion were the following: 1) The new report indicated a rate of metal allergy, in the pectus excavatum population studied in the same hospital, almost three times higher than previously reported (the previous allergy rate was 2.2%) which approached the incidence in the orthopedic literature in that institution. 2) Allergic reactions are of serious morbidity; systemic signs of dermatitis masquerade as wound infection, significant pain, limitation of activity, delayed wound healing, delay in return to school and work, and wounds issues that require repeated hospitalization and return trips to the operating room for wound care; even additional surgery for bar removal or replacement can be needed.

Strategy: Initially, the TRUE patch test was used. The T.R.U.E. ® patch test contains 23 allergens and allergen mixes that have been reported to be responsible for up to 80% of allergic contact dermatitis. Moreover, Nickel and chromium, which are elements with the highest concentration in the Nuss bar, are a part of this dermal patch test. However, since a case of a patient who was tested negative preoperatively and became positive post-operatively was identified, the T.R.U.E. ® patch test was considered to yield false negative results. In order to minimize the false negative rates with TRUE patch test, it was chosen the allergEAZE® dermal patch test which includes testing for minor components of the stainless steel bar such as copper, molybdenum and manganese, while still testing nickel and chromium.

However, no dermal patch test presently screens for all components of the steel bar and a few allergic reactions may be missed.

A postoperative allergic reaction should be suspected when a patient experiences pain out of proportion to what is expected, unexpected pleural or pericardial effusion, or a non-healing culture negative wound or rash even if dermal patch testing was negative preoperatively. The following algorithm is used for anyone suspected of having a postoperative allergic reaction:

(1) Repeat the dermal patch test. Patients must be off oral corticosteroids for at least 2 weeks prior to testing. Topical corticosteroids should be stopped at least 7 days prior.

(2) If the dermal patch test is positive or if the patient continues to have allergic symptoms, a course of nonsteroidal anti-inflammatory drugs followed by oral steroids can be helpful in relieving symptoms. The authors have been able to preserve the bar with repeated courses of oral steroids.

(3) If all attempts at preserving the bar fail, the subsequent clinical decision is to either remove the bar or exchange the bar with a titanium bar. If a bar needs to be removed prior to 2 years, a higher incidence of pectus recurrence is to be expected. Exchanging stainless steel for titanium should be treated as a recurrent pectus repair with all the inherent risks and morbidity associated with a redo repair.

Medical treatment is usually effective, and stainless steel bar removal or exchange with titanium bars is not generally necessary.

The authors explained that: While the idea of using only titanium bars in all patients may be attractive, there are a number of drawbacks to this approach. Since titanium is less malleable than stainless steel, a titanium bar must be bent using a proprietary computer assisted manufacturing technique to fit the patient's CT or MRI scan. The surface of the bar must be polished to a mirror finish to prevent tissue in growth; this is not necessary for the stainless steel bars. Modification of titanium bars during operation is difficult. Lastly, as a result of the above complexities of manufacturing, titanium bars cost roughly four times as much as a stainless steel bar. In everyday practice, where multiple bars are utilized frequently, this yields a dramatic increase in operative costs. Furthermore, if a patient expected to need two bars only requires a single bar, the second titanium bar which was not used cannot be returned to the manufacturer for use by another patient. This increases expense to the hospital. In an era of responsible medical cost containment, it makes sense to use a less expensive but equally effective product particularly when fewer than 10% of patients need the more expensive device. Furthermore, titanium usage does not preclude allergic responses since case reports of titanium allergy in other settings do exist. Though not measured in this study, the cost of treatment of postoperative allergic symptoms in patients is very likely greater than the cost of screening everyone preoperatively.

In the standard Nuss procedure, once the introducer had emerged through the left intercostal space, 2 umbilical tapes were tied to its tip and passed through the created substernal tunnel in the opposite direction serving as traction to move, from right to left in this tunnel, the previously curved bar with the convexity facing posteriorly. Antonio Messineo *et al* [1] considering this kind of passage quite difficult and sometimes dangerous, especially when fat tissue is found in the anterior mediastinum or bars with notched ends are used, proposed the traction of the bar with a tube instead of the tapes.

Technique: The patient is positioned supine on the operating table, with the chest elevated, using several blankets to allow the arms to be adducted in a lower position. The patient is intubated with a single-lumen tracheal tube and ventilated with low volumes. The most depressed area of the sternal plate and hinge points on both sides of the chest ridge are identified and marked (**Fig 44A**). A 5-mm thoracic port is bluntly introduced in a lateroposterior right position and carbon dioxide insufflated at 4 to 6 mm Hg pressure to partly reduce lung expansion. Carbon dioxide diffusion will create an operative space, allowing a clear vision of the mediastinum through thoracoscopy. Two curved lateral incisions, 3 to 4 cm long, are made just at the inferior edge of pectoralis major muscles, and a subcutaneous plane is created. If the bar overlaps the pectoralis major, its inferior bundles are released from the costal plane, thus creating a submuscular passage. An introducer is inserted into the right chest at the selected intercostal space and under-vision dissection is done just above the pericardium. This passage is facilitated by the elevation of the depressed sternum and by gas diffusion in the left pleura due to small lacerations produced with smooth dissection. Once the left side of the desired intercostal space is reached, the tip of the introducer is pushed through the intercostal space. One side of a 40-cm-long polyvinylchloride suction connecting tube (Extrudan Surgery, Birkerod, Denmark) is plugged into the introducer tip and the other side is connected to the right end of the curved bar (**Fig. 44 B-C).** The introducer is carefully pulled backward from left to right, followed by the tube, creating a path for the bar to pass with the concave side up under thoracoscopic vision **(Fig 44 D-F).** This procedure is completed smoothly and easily in a few seconds. The bar is then rotated, in the usual way, 180 degrees around its long axis, thus pushing up the sternum.

This kind of traction can be repeated as many times as needed; for example, when the bar thought proves to be too short or too long. Nowadays, bars, with or without notched ends, are available from different suppliers; in any case, a suction connecting tube is deemed useful for covering the bar edge, thus avoiding any possibility of lacerating the mediastinal fat and vessels during the operative procedure.

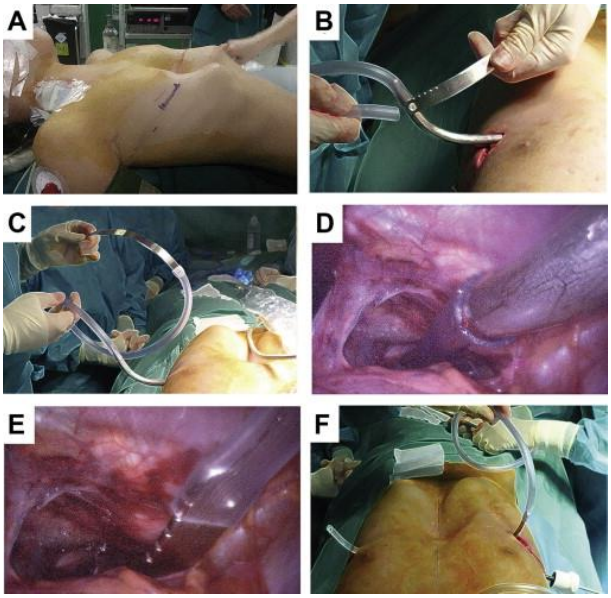


FIGURE 44

In 2015 a novel procedure that was designed according to the principle of the Nuss procedure, but a new steel bar without need for turn over was used for it was presented [25].
Bar configuration and bar accessories: A stainless steel bar is curved according to the normal structure of the human anterior chest wall. One end of the steel bar is fused with a bar stabilizer, and the other end was designed to connect with the introducer or stabilizer. The steel bars are divided into large and small sizes according to different lengths, thicknesses, and widths. The small size was often used for children, and the large size was often used for adolescents or adults. In addition, the steel bars have 15 different specifications **(Fig. 45A),** which are distinguished by the different lengths that vary from 12 to 26 cm. Each specification has a difference of 1 cm. Also, the surface of the middle part of the bar is rough to produce friction and prevent bar rotation after the operation. Bar accessories **(Fig. 45B-D)** mainly include the introducer, stabilizer, and gasket. The introducer and stabilizer are of different sizes to match the bars of different sizes. The stabilizer has a thick curved edge, which can directly transfer the supporting points of the steel bar from the intercostal muscles to the ribs. Also, the gaskets have different specifications, which can be chosen to increase the height to which the lowest point of the sternum will be elevated (thickening gasket) or to improve the length of contact surface for stabilizer and ribs (lengthening gasket).

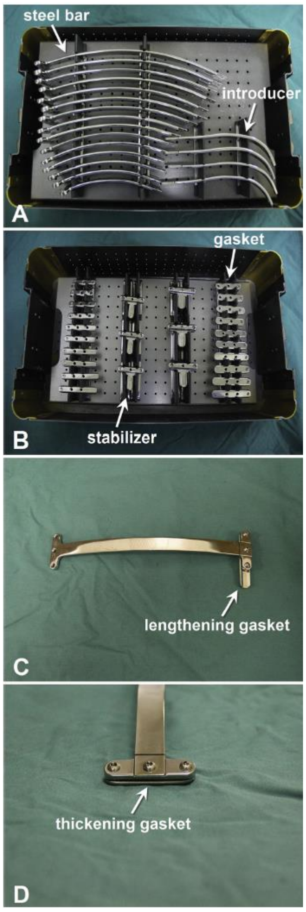


FIGURE 45. Bar configuration and accessories. (A) steel bar and introducer; (B) stabilizer and gasket; (C) lengthening gasket; (D) thickening gasket

Technique: The patient is in the supine position under general anesthesia and orotracheal intubation. The distance between the bilateral anterior axillary lines of the intercostal level corresponding to the lowest point of the sternum are measured intraoperatively, and a suitable bar was chosen. The length of the bar is 2 to 3 cm longer than the distance. A 5-mm-diameter thoracoscope is inserted into the right thoracic cavity through the right sixth to eighth intercostal space on the middle axillary line through a trocar to guide and monitor the procedure . Bilateral vertical skin incisions about 1.5 to 2.5 cm long are made near the middle axillary line. For patients with recurrent pectus excavatum, a small vertical subxiphoid anterior chest wall incision is crested to bluntly dissect the retrosternal adhesions. After the bar is tied to the end of the introducer, the introducer is inserted into the right thoracic cavity and woven behind the sternum anterior to the pericardium through the bilateral pleural cavity. The bar is pushed in and pulled out through the tunnel after the introducer and corrects the deformity without being turned over **(Fig. 46.1)**Then the introducer is removed, and a stabilizer is placed on the left side of the bar to support and fix the bar **(Fig. 46.2).** A gasket can be used under the stabilizer to increase the height to which the lowest point of the sternum will be elevated. Finally, bilateral stabilizers and gaskets are tied to the ribs and intercostal muscles with wire or suture to avoid bar rotation. Air in the pleural cavity is evacuated by producing a large tidal volume and by applying suction through the trocar. An immediate postoperative chest roentgenogram is obtained in the operating room, and the endotracheal tube is removed when the radiologic result is good. A self controlling analgesia infusion pump is used to alleviate postoperative pain for 2 or 3 days. In the authors series all patients received antibiotics intravenously for 3 days after the operation. The bar was removed between 1.5 and 4 years after placement, depending on growth.

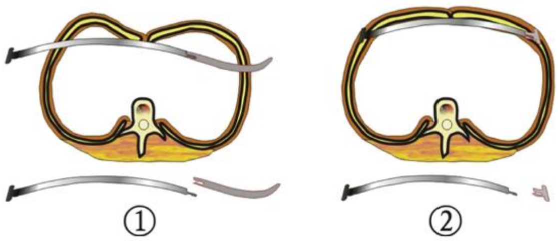


FIGURE 46. (1) The bar tied to the introducer behind sternum; (2) The bar secured with the stabilizer.

According to authors, compared with the previous Nuss procedure, the main advantages of this novel modified Nuss procedure are the following:
1. The steel bar is installed or removed by pushing and pulling through the tunnel after the introducer without flipping, which reduces the difficulty of the operation and decreases intraoperative trauma.
2. The steel bars are produced before the operation. They are divided into large and small sizes according to different lengths, thicknesses, and widths and can be used for children or adolescents and adults, respectively.
3. In the previous Nuss procedure the bar were mainly supported by the intercostals muscles, which may be an important reason for postoperative pain and significant bar displacement, especially in older patients or patients with relapsed pectus excavatum. The bar is mainly supported by the ribs in this procedure, which can effectively decrease these complications. Although bar displacement occurred in 15 patients (10.2%), only 3 patients (2.0%) required reoperation, and the bar shifted only slightly. In the authors series, some patients also felt vague pain in the early postoperative period, but the pain was mainly caused by the incisions and disappeared a few days later.
4. The elevated height of the sternum can be adjusted by changing the different gaskets. Adjusting the curvature of the steel bar is not needed. For patients with asymmetrical pectus excavatum, the more depressed side of the chest can be elevated higher than the other side with the use of the thickening gasket, and the lengthening gasket can improve the length of the contact face for stabilizers and ribs.
5. The rough surface of the middle part of the bar increases the friction between the bar and the contact tissue, and the bar has better stability.

There was no perioperative death or cardiac perforation. Bar displacement rate was 10.2% but only in 0.2% reoperation was required. During the post-removal follow-up period, results were found excellent in 90.3% of the cases and good in 9.7% of the cases. No patient had recurrence.

According to authors, this novel modified Nuss procedure is a safe, effective, and convenient treatment for pectus excavatum on condition that the following precautions are taken by the surgeon:
1. Choosing a suitable intercostal level corresponding to the lowest point of the sternum is very important for orthopedic results.
2. The length of the bar should be 2 to 3 cm longer than the distance between the bilateral anterior axillary lines of the intercostal level corresponding to the lowest point of the sternum, because the anterior chest wall will become wider after the lowest point is elevated and the stabilizer is fixed behind the anterior axillary line.
3. The bar should be kept for a longer time (3-4 years) in patients with recurrent pectus excavatum or in adult patients.
4. To prevent cardiac or vessel rupture, thoracoscopy is necessary to monitor the procedure, and a small vertical subxiphoid anterior chest wall incision should be crested to bluntly dissect the retrosternal adhesions for recurrent pectus excavatum.

Article review

Since the Nuss procedure was first presented, it has been under continuous evolution. From all the modifications that are continuously being made, surgeons around the world, chose and adopt certain modifications, not necessarily the newest ones.

Technique planification

After confirming that the patient fulfills the criteria for surgical correction as established by Croitoru *et al* [15] e Kelly [21] the surgeon must make the following considerations in order to determine the appropriate surgical approach:

The minimally invasive repair has been performed successfully on patients from 1 year to over 50 years.

The ideal age is just before puberty because at that age the chest is still very malleable, the support bar is in place during the pubertal growth spurt, the recovery time is short, and the incidence of recurrence is low.

Patients less than 8 years of age also have an excellent result and short recovery time, but because the support bar is removed before the pubertal growth spurt, there is potential for recurrence. However, if a young patient has significant cardiac and/or pulmonary compression, an early repair is justified. The family needs to be informed that the patient may require a second bar placement either at the time of removal of the first bar when a longer bar may be inserted by using a "chest tube switch technique" or later if a recurrence develops during puberty, which occurs in approximately 5% of patients.

During the first decade, it was thought that the minimally invasive procedure was only useful in prepubertal patients, but experience has shown that postpubertal patients tolerate the procedure well, and excellent results have been reported in patients in their 30s and 40s. The required force to elevate the nonmobilized sternum into the corrected position can be up to 250 N. Greater force is required for older patients. The older patients require two or more bars in more than 50% of the cases. Adults with severe pectus deformities (PI > 4.0) and asymmetric defects are at a greater risk of recurrence after a Nuss procedure. These patients may better be served with a modified Ravitch repair initially.

The ideal chest configurations for the minimally invasive repair are the diffuse "saucer shape," localized "cup shape," and symmetric funnel shape. Patients who have very steep cup-shaped depressions and patients with severe deep asymmetric "grand canyon type" depressions are more of a challenge and often require two bars. In these cases the suggestions of Park *et al* [6] may be usefull. In patients where the depression involves mostly the upper chest, care needs to be taken not to place the bar too high as it will interfere with the axilla and its vital structures. Patients who have mixed excavatum/carinatum deformities may have residual protrusion of the carinatum post bar placement, especially if there is severe sternal torsion. Park's *et al* [6] suggestions again may be taken in consideration in these cases. Older patients have a higher incidence of sternal torsion and mixed deformities, which may be a good reason to perform the repair before puberty. Patients who have a "pouter pigeon" deformity with anterior displacement of the manubrium and posterior displacement of the gladiolus develop increased protrusion of the manubrium when the gladiolus is elevated with a substernal bar. Therefore, Donald Nuss [24] does not recommend the minimally invasive procedure in this category of patients.

As far as the number of bars indicated is concerned, the following consideration should be made: Two bars are more effective than a single bar but may cause overcorrection in some patients. However, in patients with Marfan's syndrome and other connective tissue diseases who have soft bones require two bars to distribute the pressures over a wider area.

Nuss bar insertion

Technique

Positioning of the patient: The standard position is supine with both arms abducted at the shoulders to approximately 70o. Alternative method includes elevating the torso on a mattress and extending the arms posteriorly. This position allows insertion of the thoracoscope superior to the incision site. It has the disadvantage of over-extending the chest during the surgery. Another alternative position is to flex the left shoulder and elbow anteriorly, adjacent to the head, but there have been anecdotal reports of brachial plexus injury with this position. Milanez de Campos et al proposed stretching the arms along the body.

Thoracoscopy: Most surgeon use right-sided thoracoscopy, others prefer left-sided thoracoscopy, some use bilateral thoracoscopy and some insert the scope and introducer through the same thoracostomy sites. In patients with extremely deep depressions, it may be necessary to use bilateral thoracoscopy because the heart is not only compressed, but is also displaced to the left, which impedes visibility from the right. Insertion of the trocar from the left when the heart is displaced in that direction requires great caution. The trocar insertion site affects visibility. The trocar is usually inserted inferior to the incision sites, because the inferior insertion site allows for good visibility not only during the tunneling but also for suture placement during bar stabilization, but it can be inserted also through the incision site or even superior to the incision site as proposed by De Campos et al. Blunt instrumentation for trocar insertion is used and in case of inferior positioning of the trocar, it must be directed in a superior direction so as to avoid the liver and diaphragm.

The CO2 insufflation pressure should be kept as low as possible and usually a pressure of 5 mm Hg is sufficient to keep the lungs out of the operative field. When two bars are being inserted, there will be more leakage, requiring a higher flow rate to keep the pressure up.

Skin incision site: Transverse lateral thoracic incisions have the advantage of providing good access to the thoracostomy entry and exit sites, run parallel to the lines of tension (Langers Lines), rarely cause keloid formation, and require minimal subcutaneous dissection, while vertical incisions in the mid- or posterior axillary lines give poor access to the anterior chest wall and tend to cause keloid formation. When placing two or more bars, making a separate incision for each bar facilitates bar stabilization and bar removal after 3 years.

In mature female patients, the incisions should be placed in the inframammary crease between the 6- and 9-o'clock position and extended as necessary. The inframammary incisions give excellent access to the anterior chest wall, even allowing insertion of two bars, and give an excellent cosmetic result since the incisions virtually disappear.

Tunneling and sternal elevation: The thoracic entry and exit sites should be placed close to the sternum to prevent disruption of the intercostal muscles. Ideally, the tunnel should pass right under the deepest point of the depression. If the deepest point of the deformity is inferior to the body of the sternum, then the patient requires two bars: one under the sternum and one under the deepest point of the depression. The introducer should always be kept in view during tunneling. When the introducer is in position across the mediastinum, it is lifted in an anterior direction to pull the sternum and anterior chest wall out of their depressed position, thereby correcting the pectus excavatum. Repeating this lifting maneuver several times loosens up the anterior chest wall, prevents the substernal trauma and intercostal muscle injury caused by bar rotation, and minimizes the pressure on the bar, which decreases the risk of bar displacement. The pectus excavatum should be completely corrected before removing the introducer. The tip of the introducer should always be kept in sight. If the tip cannot be visualized because the depression is too deep, the scope may be inserted from the opposite side, or the first tunnel should be created more superiorly where the depression is not so deep, leaving the introducer in plasce to elevate the sternum. A 30o or flex scope is useful in this situation. Alternatively the sternum can be elevated by using the suction cup or lifting it with a towel clamp or heavy suture, or using one of the techniques that evolve "a lift system".

Bar selection: It is important to slightly overcorrect the deformity to prevent "buckling" of the anterior chest wall and to decrease the risk of recurrence. The bar should therefore have a semicircular shape with only a 2- to 4-cm flat section in the middle to support the sternum. A bar that is only bent at each end ("table top configuration") will give insufficient correction and may allow the lung to herniate between the bar and anterior chest wall. In asymmetric patients an (or two) asymmetric bar may be used as proposed by Park et al, which gives more lift on the side of the asymmetric deformity. Length bar selection is vitally important. If the bar is too short, it will be unstable. If the bar is too long, it will be unstable and will cause skin irritation. The correct length bar is usually ½ inch shorter than the distance measured from one midaxillary line to the other midaxillary line. Other surgeons prefer the Messineo *et al* technique and use an even shorter bar. To determine the right bar length, it should be bared in mind that the bar takes a slightly shorter course than the tape measurement and therefore needs to be ½ shorter than the external measurement. In children, the bars need to be long enough to accommodate growth for 2 years. The bar should not be too tight on the sides of the chest because it will cause painful rib and muscle erosion and the patient will outgrow the bar too soon, necessitating early bar removal. The pectus bars should be strong enough to support the chest in the corrected position even when the patient sustain unexpected trauma.

In patients where the depression involves mostly the upper chest, care needs to be taken not to place the bar too high as it will interfere with the axilla and its vital structures. In young patients only one bar is necessary. Adult patients, patients with Marfan syndrome, asymmetric "grand canyon type deformities, and wide saucer-shaped deformities usually require two bars. On the operating table, the correction always looks better than it does when the patient resumes normal posture because the normal thoracic lordosis is eliminated on the operating table. Donald Nuss said: "I have never regretted placing a second bar but have often regretted placing only one".

Bar stabilization: Bar stabilization is essential for a successful outcome. Initially the stabilizer was only held in position with fascial sutures, but it frequently became detached from the bar, and so it was decided to lash the stabilizer to the bar with wire sutures. However, even with the stabilizer attached, some patients dislodged their bar during the first 3 weeks before scar tissue could be laid down. Therefore, a suture around the bar and the underlying ribs through a stab wound was used; the so-called "third point fixation". Later, the five-point fixation was developed, that involves wire sutures of the bar not only with the rib above but with the rib below as well. Nowdays, most surgeons perform the "third point fixation" using not a stab wood but the lateral thoracic incisions to place the sutures. Some surgeon use wire instead of absorbable sutures, which increases the risk of injury of the underlying lung, especially if the wire fractures. An absorbable stabilizer has recently become available.

Once the bar has been stabilized, the thoracoscope must be withdrawn and the lungs must be fully reexpanded with positive end-expiratory pressure (PEEP) starting at the time the bar is being stabilized and continuing until the incision is closed. Park *et al* [37] suggest that a fine Hemo-Vac catheter is inserted in the pleural space for the potentially high-risk patients, such as adult, parallel bar technique, double bar technique, and severe asymmetry, to prevent pneumothorax. An X-ray of chest should be obtained as soon as the incision is closed. The patient is extubated in the operating room and transferred from the postanesthesia care unit to the surgical floor.
Pain management: All surgeons consider vital for the patient to have a smooth transition from anesthesia to conscious sedation. If that is not done, the bar may shift as the patient thrashes about. After the operation, there is considerable pain and discomfort and patients have a tendency to become agitated. It is better to prevent the pain cascade from being triggered in the first place, rather than reacting to it after the fact. Therefore, epidural block during anesthesia may be performed. The younger patients must be anesthetized and intubated before the epidural catheter is inserted, while the older patients may have the epidural inserted under moderate sedation and are then anesthetized. The patients must be extubated after they have been well sedated, and they should be kept sedated for the following 24 hours with morphine and fentanyle. The department staff should be instructed to keep the patients comfortable and stable overnight before slowly reducing the amount of pain medication. The epidural anesthesia should be continued for the first 3-4 postoperative days. In order to deal with the patients' anxiety in a proactive manner, it would be useful if the patients to be operated had midazolam the night before surgery and an hour before the operation. Some centers, do mild bowel preparation on day before surgery or start stool softeners and laxatives prophylactically on day 1 to prevent constipation that may occur because the patient will be immobilized and will receive heavy narcotic medication postoperatively.
Discharge: The patients should be discharged whenever they are able to walk unassisted, with analgesic and AB at home.
Follow-up: Control 7 days after operation and a month after the operation with an x-ray. Patients should return to regular activity whenever they are strong enough, which varies with age: Prepubertal children usually recover quicker and are ready to return to school in 2 weeks, whereas postpubertal patients usually require 3 weeks. All patients should be restricted from participating in sporting activities for a minimum of 6 weeks and competitive sports for 8 to 10 weeks.

Complications

Early complications (in the first month)

Early complications have been markedly reduced by meticulous attention to fitness for surgery, surgical technique, bar stabilization, evacuation of the pneumothorax, incentive spirometry, and prophylactic antibiotics.
1) The most common "complication" is an insignificant residual pneumothorax secondary to CO2 insufflation at thoracoscopy which resolves spontaneously. A chest tube is necessary very rarely; if there is an air leak because of lung injury during insertion of the trocar. There should not be a lung leak in a primary pectus repair, especially if the trocar is inserted after first creating a blunt thoracostomy.
2) Cardiac perforation. It is the most feared and severe complication. If preoperatively the heart seems sevely compressed, the sternum must be elevated with one of the chest wall elevation techniques to prevent its injury. It should be noted that, with a substernal bar in place, cardioversion requires placement of the paddles in an anterior–posterior position so that the current will be conducted through the heart. If the paddles are placed anterior and lateral, then the current will simply be conducted along the bar and not through the heart.
3) Pneumonia is rare. However, surgeons usually chose to give prophylactic antibiotics for 5-7 days.
4) Wound and/or bar infection during recovery. They can be prevented if all the precautions for foreign body insertion are meticulously adhered to. Infection requires vigorous treatment consisting of wound drainage, cultures and appropriate intravenous antibiotics, followed by long-term oral antibiotics. Treatment is usually effective in saving the bar if it is continued until the ESR and CRP have returned to normal levels. There have been reports of an increased infection rate on the side with the stabilizer.
5) Pericarditis occurs extremely rarely. The etiology is unclear. It may be due to nickel allergy, pericardial trauma, or postcardiomyotomy syndrome. A short course of prednisone is given in that case. A pleural effusion that lasts more than 4 days may be due to nickel allergy and should be treated similarly after aspirating fluid for culture to exclude infection. If symptoms occur after the prednisone has been discontinued, then the patient should be tested for Nickel allergy (if not tested preoperatively). If positive, the options are to give low-dose prednisone on alternative days until the ESR and CRP return to normal or to replace the steel bar with a titanium bar.
6) Right internal mammary laceration.(e)
7) In one case, diaphragmatic hernia occurred intraoperatively, when the central tendon of the left diaphragm was injured[54].
8) Other early complications seen are hemothorax, transient Horner's syndrome in patients with thoracic epidural analgesia catheter (occurs frequently) and transient extremity paralysis. Thoracic outletlike syndrome [52][53] and multiple ribe fractures [38] have been occasionally reported.

9) Death. In 2015 Zhang *et al* [57] reported on a 11-year-old male patient who died after he had undergone the Nuss procedure. This patient had undergone ventricular septal defect closure surgery through a sternal incision 7 years before, and although surgeons, during the Nuss procedure, created a small incision under the xiphoid process to separate the adhesion between the right atrium and sternum under thoracoscopic guidance, the right atrium was still damaged. Sternotomy and reparation of the right atrium was performed, but the massive blood loss resulted in severe hypoxic-ischemic encephalopathy and the patient died 17 days later.

Late complications

1) Bar displacement has been the biggest late challenge. In case of displacement, revision may be required. If the displacement is less than 20% and the repair remains excellent, it can be observed. If there is no further progression, then surgical revision may not be required.
2) Bar exposure. The bar may be palpable or even seen under the skin.
3) Nickel allergy, may manifest early with pericarditis or persistent pleural effusion, but may also occur late with erythema of the anterior chest wall or inflammation and drainage at the incision sites. The inflammation and drainage may resemble a chronic infection, but cultures are negative and testing for nickel allergy will give a positive result. Attention has to be made because there have been reported cases of patient with negative allergy tests preoperatively who were found positive to allergy tests postoperatively. Treatment consists of local wound care and a short trial of prednisone. If the patient responds, then low-dose alternate day prednisone until the ESR and CRP are back to normal will usually resolve the problem. If the patient responds to the steroid therapy, the bar can be left in place until it is time for removal. If the patient does not respond to treatment, then the steel bar needs to be replaced with a titanium bar. In 2014 Shah *et al* [22] proposed a broad metal allergy test as a routine preoperatively.
4) Overcorrection, resulting in pectus carinatum is severly unfrequent. It may occur in patients with Marfan syndrome or very deep cup-shaped deformities. Early bar removal or an external pressure brace may be required. Some surgeons have reported on carinatum developing in patients with asymmetry and a twisted sternum.
5) Undercorrection not only predisposes the patients to increased risk of recurrence but also results in abnormal ridges developing adjacent to the sternum because there is not enough space. The cartilaginous portion of the rib will buckle under the pressure.
6) Assymetry of the chest wall that may require reoperation.
7) Significant adhesions of both lungs to the bar is a common finding during bar removal operation. Trapped (lower lobe) that led to ventilatory restriction and required early bar removal and thoracoscopic decortication has been described.
8) Chronic constrictive pericarditis that may require pericardiectomy.
9) Persistent pain may be due to bar displacement, stabilizer dislocation, bar too tight, bar too long, sternal or rib erosion, infection, or allergy. An anterior and lateral chest x-ray, complete blood count, ESR, CRP, and T.R.U.E. patch for allergy will identify the cause and allow appropriate treatment. Reoperation has been needed in some cases because of skin perforation by a protruded stabilizer [31].
10) 1 case of bilateral anterior sternoclavicular dislocation a month after reoperation for bar displacement has been reported [38].
Other uncommon complications reported are sternal erosion and anterior thoracic artery pseudoaneurysm [52].

Bar removal

The bar should remain in the chest for 2 to 4 years after surgery. If the patient grows more than 6 inches (13cm) after the bar insertion and becomes symptomatic with lateral chest pain, then he needs to be evaluated to see whether early bar removal is required.

Technique

Bar removal is accomplished under general anesthesia with positive pressure ventilation and 5 to 6 cm of PEEP to prevent pneumothorax. Both sides of the bar should be mobilized, and the bar should be unbent by using either the bar flippers or small bar benders. The complete bar alignment is important because, first it facilitates the bar sliding, and second, a curved incompletely rectified bar acts as a 'hook' and results in haemorrhage. After straightening, the bar is removed very slowly while monitoring the EKG and all the other vital signs. The serrated edges of the bar could be covered by a film protector as proposed by De Campos *et al*. A postoperative chest radiograph is necessary routinely to check for pneumothorax.

Complications

1 case of massive bleeding because of injury of a segment artery of the right lower lobe that occurred while the bar was being removed during reoperation for bar dislocation, recurrence of the PE, chest pain and backache, has been reported by Leonhardt *et al* [38].

Long-term results

Patients with an asthenic build and a light bone structure are much easier to treat than patients with a mesomorphic build and heavy bone structure. Long-term results after bar removal have shown that if the bar is left in place for 2 years or more, the excellent long-term results achieved at the time of the repair are maintained after bar removal. If the bar is removed before 2 years, the reccurence rate increases inversely with the length of time the bar remains in situ. The age at the time of repair affects recurrence rate. If the bar is removed before puberty, there is increased risk of recurrence. All patients should be encouraged to exercise regularly starting 2 months postoperatively. It is considered that patients who exercise regularly are more likely to maintain their excellent result than patients who are sedentary and rarely expand their chest in full capacity.

Postoperative cardiopulmonary function studies have shown good improvement in some studies and less in other studies. The reasons for this discrepancy are multifactorial and include the size of the cohort being studied, the duration of the study, the severity of the pectus excavatum, whether the studies were done during exercise or at rest, etc. In Postoperative cardiac studies have shown an increase in cardiac filling and stroke volume postoperatively.

Cosmetic results should be not only valued but also considered the best indication of therapeutic success.

Conclusion

Studies have confirmed that the various modifications of the Nuss procedure have achieved a reduction in the complications rate and better cosmetic result over the years. Quality of live studies and overall patient satisfaction studies have shown a significant improvement in self-esteem and a 95% overall patient satisfaction rate.[24] As far as adults are concerned, there is still no consensus about the best procedure to use: The Ravitch or the Nuss. According to Hanna [58 “there will always be 2 good methods to repair a PE in adults, the Nuss procedure and the Ravitch technique. Each has its advantages, and neither is strictly superior to the other in long-term outcomes”.

Our experience

Over the years, an increasing number of patients with depression of the anterior chest wall chose the Meyer Childrens Hospital of Florence for diagnosis and treatment. Recently a PE center was formally established in this hospital. In most of the cases, the diagnosis is made by the pediatrician who guides the patient seeking treatment.

First office visit

Whether to perform or not the Nuss procedure, is decided according to the criteria established by Kelly [21]. In selected cases, an MRI (ex. suspect of Marfan syndrome) or a CT scan is necessary for decision making. Genetic tests are necessary in case a syndrome like Marfan, Noonan or Poland is suspected.

In very young patients with mild PE, the use of the Vacuum chest wall lifter is proposed, in an effort to correct the deformity.

In very young patients with severe PE, the use of a Vacuum chest wall lifter is proposed in an effort to repair the deformity in mild PE and mobilize the chest ridge before the Nuss procedure that will necessarily be performed around age 12.

If the Nuss procedure is decided, the surgeon explains the operation and the expectations it forms for the final result to the patient (and his parents).

Preparation for surgery

All patients are encouraged to start an exercise program and respiratory fisiotherapy before surgery. Patients who have received treatment with the Vacuum chest wall lifter should continue the treatment until the day before surgery. Blood tests, allergy tests to Nickel, an X-ray, spirometry and cardiological evaluation with cardiogram end echocardiogram form the standard preoperative assessments. In case a patient is considered allergic to Nickel, a titanium bar must be used. This requires advanced planning as the bar needs to be ordered from the manufacturer before surgery. In order that the bar can be prebent and polished, to prevent tissue adherence, the manufacturer will need to know the length of the bar required and a copy of the CT scan at the insertion site.

MATERIALS AND METHODS

From the 1st of January 2013 to the 21th of July 2016, 105 patients (32 children, 80 adolescents and 3 adults) underwent the Nuss procedure in the Pediatric Surgery department of Meyer hospital (in this study are not included one patient who underwent surgery for chest wall reconstruction along with Nuss procedure during this period, redo surgeries of patients who had surgery before 2013 or in other institutes, bar removal surgeries of patients who underwent the MIRPE before 2013, and the adult patients who were evaluated in Meyer hospital but were operated on by the same team of surgeons in Careggi hospital, Florence). The average age at the time of surgery was 16,6 years; male patients were five times as many as female patients (table 3). The highest Haller index was 23,6. Among patients, there was an adolescent with Currarino-Silverman type of PE and an adolescent with Marfan syndrome.

Table 3 Relevant calculations

Variable	
Mean age (years)	16,6
Male/female	88/17 (83%/17%)
Patients with single Nuss bar	72
Patients with two Nuss bars	33
Bars without stabilizer	4
Titanium bars	1
Mean bar length (range) (inches)	10.5 (8-13)
Mean operative time (range) (min)	87.7 (35-210)
Mean length of hospital stay (range) (days)	7,11 (3-15)

In the Pediatric Surgery Department of Meyer University Hospital of Florence, the standard surgical technique is the following:

The patient is positioned supine on the operating table, with the chest elevated, using several blankets to allow the arms to be adducted in a lower position. The patient is intubated with a single-lumen tracheal tube and ventilated with low volumes. The most deepest point of the depression and hinge points on both sides of the chest ridge, are marked this way: We mark the deepest point of the chest depression with an X using a marking

pen. This point sets the horizontal plane for bar insertion . We follow this horizontal plane laterally to the top of the pectus ridge anteriorly where we select and mark the intercostal spaces to be used for bar insertion as close to the horizontal line as possible, making sure that the line is not below the sternum. If so, we move the horizontal line superiorly so that it passes superiorly to the lower end of sternum. We mark an X on the skin where the bar should enter the intercostals space (the hinge points), in line with the deepest point. After marking the X for the hinge points, we continue in the same horizontal plane down the lateral chest wall on each side, and draw transverse lateral thoracic lines on the anterior axillary line. We make sure that the transverse lines are in the same plane as the X marked in the deepest point of the pectus and the Xs marked at the top of the pectus ridge. We make two curved skin incisions, 3 to 4 cm long as marked and we create a subcutaneous tunnel up to the determined points on the chest ridge. If it seems that the bar will overlap the pectoralis major, its inferior bundles are released from the costal plane, thus creating a submuscular tunel. In the meantime, the appropriate bar has been chosen (half an inch shorter than the distance between the two mid-axillary lines) and has been bended with the Zimmer bar bender to conform to the desired chest wall curvature (in case of steel bar). If pectus excavatum is asymmetrical, as per Park *et al* method, we conform the bar following the asymmetry of the chest (in case that a titanium bar is needed, it is used configurated by its manufacturer).
Next, a 5-mm thoracic port is bluntly introduced in a lateroposterior right position 2 intercostal spaces above the skin incision, and carbon dioxide insufflated at 4 to 6 mm Hg pressure to partly reduce lung expansion. Carbon dioxide diffusion will create an operative space, allowing a clear vision of the mediastinum through thoracoscopy. A 5-mm thoracoscope is inserted through the port to verify the deepest point of the sternal depression and to monitor the procedure, while another incision is made to the opposite side for the introduction of the thoracoscope on the left side later. An introducer is inserted into the right chest through the right skin incision to dissect the plane separating the sternum from the pericardium, under close vision and it is exteriorized on the left side through the skin incision. This passage is facilitated by gas diffusion in the left pleura due to small lacerations produced with smooth dissection. In the event that during the passage the introducer's tip cannot be kept in perfect sight, we use the thoracoscope to control its tip from the left hemithorax. One side of a 40-cm-long polyvinylchloride suction connecting tube (Extrudan Surgery, Birkerod, Denmark) is plugged into the introducer tip and the other side is connected to the right end of the curved bar. The introducer is carefully pulled backward from left to right, followed by the tube, creating a path through the dissected plane for the bar, which passes with the concavity facing anteriorly. The bar is then rotated with the use of a "flipper" 180 degrees around its long axis, thus pushing up the sternum. If the bar is straighten out, we increase the curvature as appropriate (not too much). Stainless-steel stabilizers are routinely inserted on one or both sides of the bar, as close as possible to the bar end; we prefer a single stabilizer for very young patients. The stabilizers are secured with pins and are eventually fixed to intercostal muscles by interrupted polyglactin sutures. An additional bar is introduced if the cosmetic result is unacceptable with a single Nuss bar, and a single stabilizer per bar is placed on opposite sides. We control both hemithoraxes thoracoscopically. If everything is normal, the thorascope is withdrawn, the lungs are fully reexpanded and positive end-expiratory pressure (PEEP) is applied so that the CO_2 is eliminated. The incisions are closed after pulling the chest wall muscles over the stabilizer and the bar edge, so that the complex bare edge-stabilizer does not irritate the skin.
Chest x-rays are routinely taken while the patient is intubated postoperatively, to exlude hemothorax or pneumothorax, to document the result of the procedure and to allow assessment of the position of the bar during the follow-up period.

Postoperative pain

Postoperative pain is managed with epidural analgesia and nonsteroidal antiinflammatory drugs. Morphine is used for breakthrough pain and the epidural catheter is usually removed on the third postoperative day. The prophylactic treatment with antibiotics that started intraoperatively, continues for a week after surgery.

Ambulation

The patient is first mobilized by sitting in the bed flexed at the hip level, keeping the back straight. Then, he should maintain a straight back for as long as possible and avoid sitting in the bed with thoracic spine flexed. Ambulation is encouraged whenever the patients are strong enouph. They usually need assistance in getting out of the bed the first few times. We discharge the patient home whenever he is able to walk unassisted with analgesic/nonsteroidal antiinflammatoty medicines (oxycodine and ibuprofen) for pain**,** and antibiotics.

RESULTS

72 patients received a single Nuss bar and 33 patients received double Nuss bar. In all cases but one (a single titanium bar), steel bars were used. No blood transfusion was needed. The average bar length was 10,5 inches (8-13). Only four bars were secured without a stabilizer. Average operative time was 87,7 min (range, 35 to 210 min) and the length of hospitalization varied from 3 to 15 days with an average length of stay of 7,11 days (table 3).

Complications

There have not been any intraoperative complications. The complications identified during hospital stay and follow-up are shown on table 4. There has been no mortality. In no case did heart injury occur.

A pneumothorax was visible in 59 cases (56%) but only 9 cases required chest tube insertion (8%). In a patient who had one bar-one stabilizer and developed hydropneumothorax on one side and pneumothorax on the other side, redo surgery was performed to add a second stabilizer to the bar and place a second bar with one stabilizer.

In one patient who had two bars, lareral sliding of the lower bar occurred; redo surgery for positioning the stabilizer more medially and remodeling the bar was required.

In another patient who had two bars, the lower bar was removed 3 months after insertion because of displacement and chest pain.

In one case of bar shifting, surgery was performed to straighten the bar and add a second bar with a stabilizer.

In a case of severe chest pain, surgery was required to free the major pectoralis from attachments

A patient developed empyema and had his bar removed six months after insertion.

Another patient had persistent severe chest pain; the bar was removed a month after insertion because it seemed to compress the left lung lower lobe.

Removal of one of the two bars a month after insertion was required in a case of persistent massive pleural effusion.

There has been a single case of seroma and the patient was treated surgically few times in the attempt to solve the problem.

Table 4 Complications of the Nuss procedure in this series

Complication	No of patients	%
Heart injury	0	
Death	0	
Pneumothorax	59	56%
requiring surgery	1	0,9%
Hydropneumothorax requiring chest tube insertion	3	2,8%
requiring redo surgery	1	0.9%
Pleural effusion requiring chest tube insertion	3	2,8%
requiring bar removal	3	2,8%
Empyema requiring bar removal	1	0,9%
Persistent chest pain requiring revision of the thoracic wound	4	3,8%
Bar exposure requiring surgery	1	0,9%
Bar displacement**	4	3,8%
requiring redo surgery	3	2,8%
requiring bar removal *	1	0,9%
Seroma requiring surgery	1	0,9%

Only the lower bar was removed

****We classify "bar dislocation'' as an altered, flipped position of the bar on a lateral chest x-ray**

Follow-up

The follow-up protocol includes outpatient visits at 1 month with an X-ray, at 6 months, and then annual visits for the following 3 years. Light physical activity is reintroduced a month after surgery, and more rigorous sports (except contact sports) are allowed after 6 months. The young patient is permitted to carry school bag on the back only three months after surgery. The mean follow-up time up in this series has been 31 months.

Bar removal

The desired length stay of the bar is 3 years. An X-ray is taken before removal, to allow evaluation of the bar position and assessment of the correction during the post-removal follow-up. In this series, of the 115 patients who had surgery, only 6 of them have had their bar removed.

Technique

Bar removal is performed without flipping it. The ends of the bar are mobilized and straightened out with the use of a flipper. Next, the stabilizers are removed and a medium-sized bone hook is used to pull one end of the bar, which passes smoothly between the pericardium and the sternum.

In selected cases, once the bar is removed, lipofilling is performed intraoperatively to complete the cosmetic result: Fat is drained from the hips or the abdomen and is placed subcutaneously to fill in any minor chest depression or asymmetry that may remain after bar removal.

Results

The post-removal follow-up consists of an outpatient visit at 1 month and 1 year after removal with an X-ray. All patients are encouraged to do intensive exercise and fisiotherapy for the subsequent years. In this series mean post-removal follow-up time is 5,5 months (up to date). Patients were photographed before insertion, before removal and after removal. All six patients who had their bar removed, had excellent result during the 1 month post-removal follow-up, the two patients who had their bar removed earlier than scheduled included. These two patients had an additional 5 month post-removal follow up some days ago that showed maintenance of the excellent correction.

CONCLUSIONS

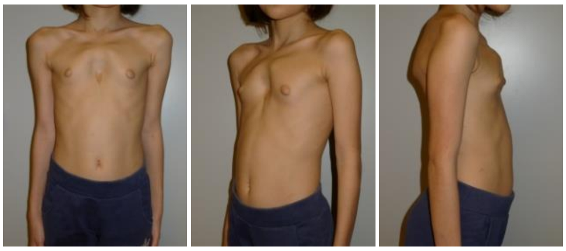
Bilateral thoracoscopy, tunneling and maneuvers for chest wall elevation have minimized the risk of heart and vessels injury. Death rate is extremely low. The use of lateral stabilizers and shorter bars and the various fixation techniques such as the five-point fixation technique, have led to sharp drop of the bar displacement rate. Pneumothorax, which is the most common complication, it is caused by the residual gas used during thoracoscopy and it resolves spontaneously in most of the cases. The use of asymmetric bars has extended the excellent cosmetic results to patients with severe PE and to adults. Bar removal is generally performed without complications.

The Nuss procedure came as a revolution in the treatment of Pectus Excavatum in 1998 and due to its continuous evolution has become the cornerstone of the repair of PE.

Our case presentation

The cases below have been chosen to present, with visual material, surgeons experience with treating PE in the last 31 months in the Pediatric Surgical Department of Meyer Hospital, Florence, Italy (the photos come from Prof. Messineo and Dr. Facchini personal archive).

Case 1



A case of Currarino-Silverman PE.

Case 2

A case of PE associated with mammary asymmetry.
In this case, plastic surgery has been decided to correct both breast asymmetry and PE: The deepest point of the chest depression will be filled with fat (fat grafting) to correct PE. A breast prothesis will be placed on the right while on the left mastopexy will be performed.

Case 3

In this case, the clinical quantification showed mild PE.

Case 4

The hinge points, the sites of the bar edges and the stabilizers are marked preoperatively.

Case 5

A longer and a shorter bar are tested as options before surgery.

Case 6

During this sugery:

The arms are stretched along the body and blankets are placed under the back as described by Engum *et al.*

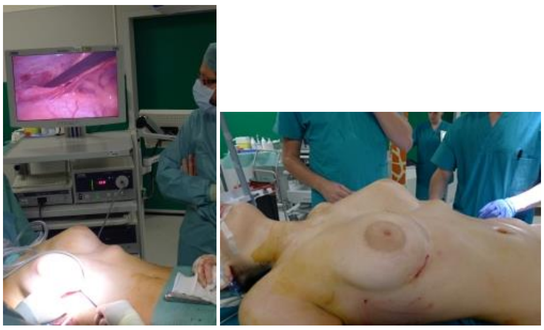
The "skin flaps " are created medially as proposed by Pilegaard *et al*.

The bar has been bent to adjust better to the conformation of the thorax as proposed by Park *et al*.

One side of a suction connecting tube is plugged into the introducer tip and the other side is connected to one edge of the bar. Thus the introducer pulles the connecting tube which is followed by the bar, as described by Messineo *et al*.

A “bone hook”pulls the bar from the right side completing its traction after the chest tube has been removed.

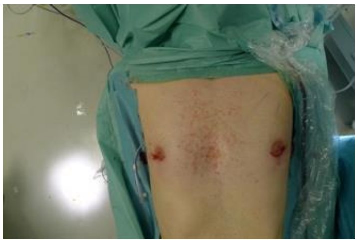
The stabilizer is secured to the bar with a steel wire suture.



Case 7

Bilateral thoracoscopy is performed.

In the past, before Messineo *et al* developed their “tube bar-traction maneuver”, umbilical tapes were tied to the tip of the introducer to guide the bar under the sternum.

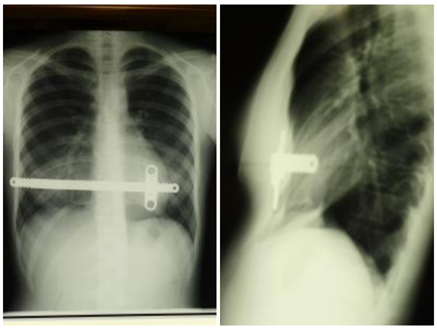


A chest tube is placed in this patient for the fear of residual pneumothorax as indicated by Park *et al*.

Case 8

Preoperatively.

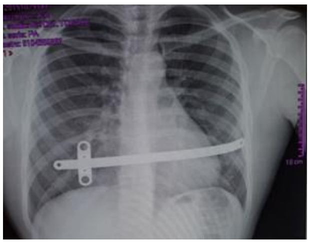
1 month follow-up.



During surgery a single stabilizer was considered sufficient for bar fixation.

8 month follow-up.

Case 9

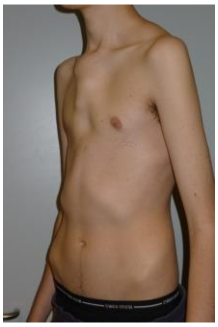


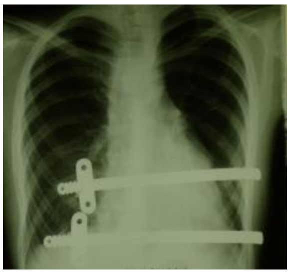
Preoperatively.

1month follow-up

Case 10

This is a case of Marfan syndrome with PE.





Preoperatively

Two bars are usually used in Marfan syndrome.

Case 11

Preoperatively.

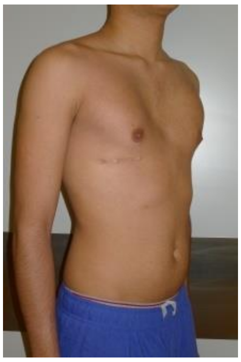
2 month follow-up: Orthosis for protruded lower ribs was required. The correction of the upper ribs caused protrusion of the lower ribs as Park *et al* described that it may occur.

9 month follow-up.

Case 12

In this patient, resection of seroma was performed eight months after surgery. A few months later recurrence was observed. All cultures were negative and the patient had been found negative for allergy to Nickel before surgery. During bar removal, two years and half after insertion, the seroma was resected again. Post-removal follow-ups showed good healing.

Case 13

Planification for lipofilling during bar removal. Autologous fat will be used.

2 month post-removal follow-up.

NOTES

(a) From 1987 to 1990 the sternum and lowest costal cartilages were exposed through an anterior thoracic incision. The Kelly clamp was advanced under the sternum under direct vision without mobilizing, incising, or excising any of the rib cartilages. However, this approach had the disadvantage of difficulty in obtaining sufficient lateral exposure for bar stabilization. Also, the excellent correction of the deformity caused tension on the anterior thoracic incision, causing an unsightly scar. Therefore, having established that one could achieve excellent correction of the pectus excavatum deformity without rib resection and sternal osteotomy, since 1991, the bar through was inserted through the lateral thoracic incisions as described above.

(b) Nuss and his colleaugues started the routine use of thoracoscopy in 1998 after they had seen a single case of cardiac perforation during a visiting professorship at another institution. Immediate sternotomy and repair was performed.

(c) Initially, for adults the double bar technique was developed. Subsequently, the compound bar technique was tested and proved to be even more effective.

(d) Pilegaard *et al* had suggested the medial positioning of a stabilizer. At that time, a shorter bar was needed, so that the stabilizer could be positioned medially. Later, De Campos invented the grooved stabilizer, that can be placed medially no matter how long the bar is.

(e) According to Messineo *et al* [1] the first major complication during a bar passage was reported by Banever and colleagues, who described a right internal mammary laceration.

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