Modified minimally invasive pectus repair in children, adolescents and adults: an analysis of 262 patients

Alexander M. Rokitansky, Rainer Stanek

Correspondence:
Alexander M. Rokitansky, Department of Pediatric Surgery Donauspital / SMZ-Ost / Vienna, Langobardenstrasse 122, A – 1220 Vienna
e-mail: alexander.rokitansky@wienkav.at
www.kidsdoc.at

Abstract

In order to achieve safe and successful funnel chest treatment even in older patients and reduce postoperative complications, we modified the procedure of minimally invasive pectus repair using the single-piece pectus bar (PSI® Hofer Medical, Austria) with no metal abrasion. The features of modified minimally invasive funnel chest correction (MMIPR) are the following: (a) additional subxiphoidal incision, (b) anterior mediastinal-mediastinoscopic mobilization, (c) mediastinoscopy, (d) elevation of the funnel during pectus bar placement, and (e) fixation of the implant ends in a latissimus dorsi *muscle bag, below the anterior margin of the muscle. In older funnel chest patients with a stiff thorax, a curved sternum, marked asymmetry or a mixed pigeon/funnel chest, the minimally invasive correction method has to be supplemented by additional surgical measures (MEMIPR) such as partial sternotomy (23%), slit-rib chondrotomy under thoracoscopic guidance (Rokitansky method; 48%), rib resection (5%), and occasionally rib osteotomy. In 8 patients with residual minor deformities we administered an ultrasound-guided Macrolane® injection (5 to 20 cc). 262 patients (mean age: 17.7±7 years) were eligible for analysis. The large majority of them underwent MIPR between the age of 14 and 20 years; 6 patients were older than 40 years. The pectus bar implant was left in the chest for a period of 1.4 to 6.5 years. Modified minimally invasive pectus repair (MMIPR) was performed in 121 patients (mean age: 15.2±5 years). The majority of patients received one pectus bar; 13.2% received two bars. Modified extended minimally invasive pectus repair (MEMIPR) was performed in 141 patients (mean age: 22.5±8 years); two pectus bars were used in 58.1% of cases. We observed no bar dislocation. Minimal bar movements were noted in 1.6% (MEMIPR) and 4.9% (MMIPR) of cases. With the MEMIPR technique, subcutaneous hematoma was observed in 4.1% of patients. No re-thoracotomy was required in the 262 patients who underwent MMIPR or MEMIPR. After a mean period of 3.4 years the implants were removed surgically in 103 patients; recurrences were observed 0.9%. Our procedures of MMIPR and MEMIPR with a single-piece pectus bar permitted safe and successful surgery in patients who required complex funnel chest correction.*

Keywords: *pectus excavatum, modified extended minimally invasive repair, Rokitansky method, older patients, adults*

Rezumat

Tehnică minim-invazivă modificată de corectare a deformărilor toracice la copii, adolescenți și adulți: analiză pe 262 de pacienți

Pentru un tratament reușit și fără riscuri al deformărilor toracelui „în pâlnie" chiar și la pacienți de vârstă mai mare și pentru reducerea complicațiilor postoperatorii, am modificat procedura minim invazivă de reparare a toracelui prin utilizarea unei singure lame fără abraziune metalică (PSI® Hofer Medical, Austria). Etapele tehnicii minim-invazive modificate de corectare a toracelui „în pâlnie" (MMIPR) sunt următoarele: (a) incizie subxifoidiană adițională, (b) mobilizare mediastinală anterioară mediastinoscopică, (c) mediastinoscopie, (d) ridicarea sternului înfundat în timpul poziționării barei toracice și (e) fixarea capetelor de implant într-un lambou muscular din mușchiul latissimus dorsi, *sub marginea anterioară a acestui mușchi. La pacienții mai vârstnici cu torace rigid și stern mult deformat, asimetrie marcată sau deformare mixtă tip* pectus arcuatum, *intervenția corectivă minim invazivă trebuie suplimentată cu metode chirurgicale adiționale (MEMIPR), cum ar fi sternotomia parțială (23%), condrotomie sub ghidaj toracoscopic (metoda Rokitansky, 48%), rezecție costală (5%), ocazional osteotomie costală. La 8 pacienți cu modificări reziduale minore am administrat injectabil sub ghidaj ultrasonografic Macrolane® (5 - 20 cc). 262 de pacienți (vârsta medie: 17.7±7 ani) au fost eligibili pentru analiză. Majoritatea au fost supuși MIPR în intervalul de vârstă 14-20 de ani; 6 pacienți aveau peste 40 de ani. Bara toracică implantată a fost lăsată în torace pentru o perioadă între 1,4 și 6,5 ani. Tehnica minim invazivă modificată de corecție a toracelui (MMIPR) s-a realizat la 121 de pacienți (vârsta medie: 15,2±5 ani). La majoritatea pacienților s-a montat o bară toracică; la 13,2% au fost folosite două bare. Tehnica minim invazivă extinsă (MEMIPR) a fost efectuată la 141 de pacienți (vârsta medie: 22,5±8 ani); s-au folosit două bare toracice la 58,1% din cazuri. Nu am observant nici un caz de dislocare a barei. Deplasări minime ale barei au fost observate la 1,6% (MEMIPR) și respectiv la 4,9% (MMIPR) din cazuri. În cadrul tehnicii MEMIPR s-au observat hematoame subcutanate la 4,1% din pacienți. Nici unul din cei 262 de pacienți care au fost supuși MMIPR sau MEMIPR nu a necesitat reintervenție. La 103 pacienți, implanturile au fost înlăturate chirurgical după o perioadă medie de 3,4 ani; recidivele au fost observate la 0,9% din cazuri. Procedurile noastre MMIPR și MEMIPR cu o bară toracică dintr-o singură piesă permit efectuarea de operații reușite și sigure la pacienți care necesită intervenții complexe de corectare a deformărilor toracice „în pâlnie".*

Cuvinte-cheie: *pectus excavatum, corectare minim-invazivă modificată extinsă, metoda Rokitansky, pacienți vârstnici, adulți*

Introduction

Pectus excavatum is the most common deformity (1: 400-1000 births) of the anterior chest wall, characterized by a sternal depression beginning over the midportion (second and third rib) of the manubrium and progressing inward through the xiphoid process[1, 2]. The sternum may be straight or curved. The distal end of the sternum is usually depressed and the ribs are markedly involved in the formation of a funnel. As a rule the fourth to seventh rib is affected; in some cases the third rib may also be involved. Younger patients have a symmetrical funnel chest, whereas older patients tend to have asymmetrical forms. Thus, the deepest point is on the right side in paramedian location, adjacent to the tilted sternum. On the left side of the chest the heart offers relative resistance and hinders further intensification of the funnel. The older the patient is, the more pronounced is the kinking in the cartilaginous as well as bony portion of the ribs **(Figure 1)**.

In one-third of patients the funnel-shaped depression of the anterior chest wall, which is a disturbing cosmetic feature, starts to become visible in the first twelve months of the child's life. Spontaneous remission is very rare, especially after the age of six years. The thesis that a funnel chest will resolve on its own is usually erroneous.

The cause of this deformity of the rib cage is still not clear. A positive family history indicative of a familial predisposition is found in just one third of patients (37%)[3-5]. However, no specific genetic triggers for abnormal cartilage growth in isolated pectus excavatum have been identified thus far[6]. Connective tissue diseases such as Marfan syndrome, osteogenesis imperfecta, or Ehler Danlos syndrome have been reported in connection with a funnel chest[7]. Relevant factors in the pathogenesis of this condition include changes in the mechanical load-bearing capacity of the sternum, developmental disorders of the diaphragm, and a tendency towards longitudinal growth in the region of the rib cartilage.

The male sex is predominant, the male-female ratio being approximately 3:1. A pectus excavatum is not merely a matter of cosmetic appearance. Concomitant pathologies occur in approximately 20% of children, scoliosis being the most common one (10-39%)[2, 8, 9]. In less than 10% of cases one finds a prolapse of the mitral valve[10, 11]. The latter is also discussed in association with the altered geometry of the valve secondary to compression. The right ventricle may be dented because of the depressed sternum[12]. In some patients we found a mild tricuspid insufficiency. The presence of Marfan's syndrome must be included in the differential diagnosis. Ventilatory deficits in the lower lobes of the lung may occur in more severe forms of the condition and may be corrected by surgical repair[13, 14]. Furthermore, the patients typically have weak muscles in the back and the shoulder, and demonstrate poor body posture. The abdomen is usually protruded in a globular fashion. In addition to the classical pectus excavatum, asymmetrical and mixed forms such as the funnel-chicken chest also exist.

Physical symptoms and findings

Intolerance of exertion, chest pain, poor endurance, and shortness of breath have been reported[15]. While young children are less likely to demonstrate these symptoms, the latter may develop or worsen during adolescence.

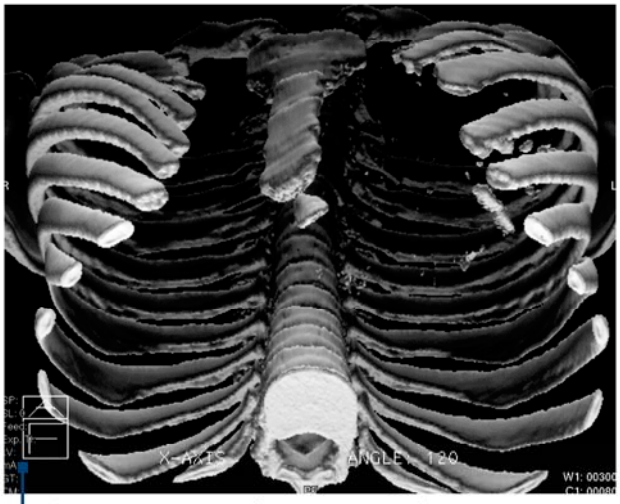

Figure 1. *3D CT scan of an asymmetrical pectus excavatum; in older patients the bony portion of the rib is bent and one commonly finds a rotated sternum*

Pectus excavatum patients have a reduced physical endurance capacity which, in our experience, becomes especially evident around the age of 40. The patients usually have no symptoms at rest or during mild or ordinary strain, but experience difficulties under greater physical strain such as sports. During pursuing sports that strain the upper extremities, the upper trunk and the shoulder girdle, patients report a sensation of pressure or a tearing pain in the pectus excavatum region. In some cases the main symptom is dyspnea. Those with more severe funnel deformities are much more likely to experience diminished lung function with a restrictive pulmonary pattern and a moderately reduced vital capacity[16]. Several authors have reported an improvement in respiratory function after correction of funnel chest, although respiratory function prior to pectus bar explantation might remain impaired[12, 13, 17-20].

Severe forms of the disease are commonly associated with cardiac displacement to the left, subtle right ventricular outflow obstruction, and reduced right ventricular systolic function[21,22]. The patients' ejection fraction is improved by the increase in heart rate. Baseline cardiac index values were normal in children with pectus excavatum, albeit 45.5% of them showed a limited response to exercise. Pectus excavatum repair improves these values[22-29].

Cardiac arrhythmias may also occur, especially when the patient flexes the torso ventrally and the heart is in close mechanical contact with the sternum. In terms of subjective symptoms, palpitations have been reported in many cases.

Psychological symptoms

As in certain other malformations, psychological problems cause difficulties for children and adolescents. Adolescents experience psychological difficulties to a significant extent. Owing to the "hole in the chest", patients are greatly impaired in their self-esteem, especially because their peers openly refer to the deformity. The beneficial effect of

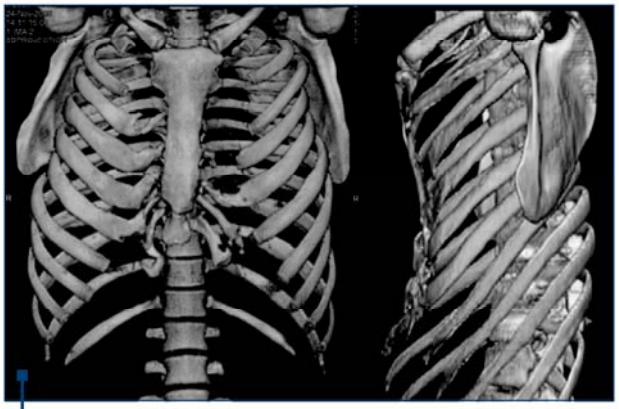

Figure 2. *3D CT scan of a recurrent pectus excavatum with calcification in the cartilage parts of the ribs*

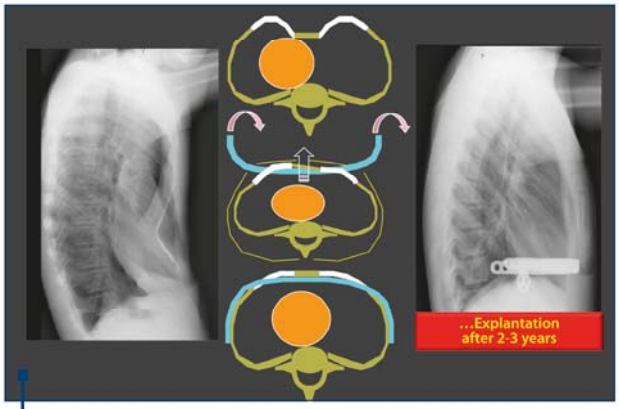

Figure 3. *Principle of the minimally invasive pectus repair (MIPR)*

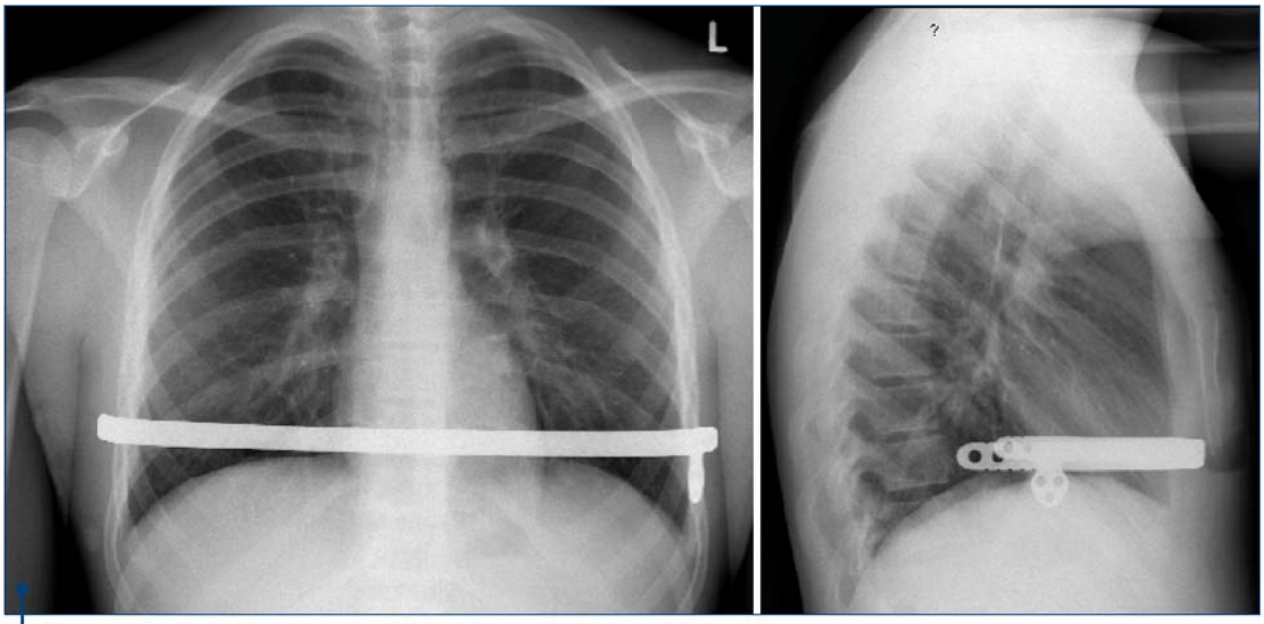

Figure 4. *The single piece pectus bar (PSI®– Hofer medical, Fürstenfeld, Austria)*

the surgical procedure on loss of self-esteem and a poor body image has been mentioned in several studies[30, 31].

Diagnostic procedures

Physical examination using the pectus bar template provides the investigator with an initial impression of the patient's condition. A distinction is made between narrow canyon-shaped funnels on the one hand, and wide types on the other. Canyon funnels with a depth exceeding 4 cm are much more difficult to correct. The clinical investigation is usually followed by a conventional chest X-ray and a sectional imaging procedure (preferably MRI, occasionally CT), especially in asymmetrical forms of the disease[32, 33]. In certain cases a 3-D CT reconstruction is useful for preoperative planning, especially in older patients (calcification of rib cartilage) and in cases of recurrence **(Figure 2)**[34].

A number of indices were developed to quantify the pectus excavatum objectively; the Vertebral Index (VI) and the Haller index are most frequently used[35-37]. VI is calculated on the basis of a lateral X-ray alone. Its low radiation exposure makes it a preferred investigation for postoperative follow-up. A cardiac ultrasound scan identifies valve insufficiencies or the frequent mitral valve prolapse while an ECG (Holter ECG in different positions) will demonstrate arrhythmia. Spirometry is performed to determine lung function, and usually reveals a restrictive pulmonary pattern[38].

Therapeutic measures

Minimal access pectus repair, first described by Donald Nuss in 1998, has become the "gold standard" for surgical repair of the funnel chest[15, 39, 40]. Procedures that elevate the sternum by thoracoplasty should clearly be given preference. Subcutaneous implantation of an artificial prosthesis (a pectus insert) for cosmetic purposes is disadvantageous because of the child's growth and the cardiorespiratory morbidity of the procedure. The "pectus excavatum plastic cushion" fails to hinder the advancement of the funnel chest or the progression of physical symptoms. The cosmetic outcome of synthetic implants in the long term is frequently unsatisfactory.

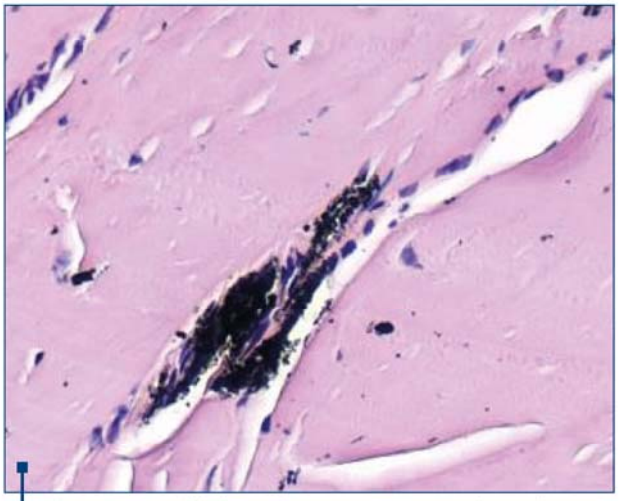

Figure 5. *Metal debris in the scar tissue around a multipart Pectus – Bar (HE staining)*

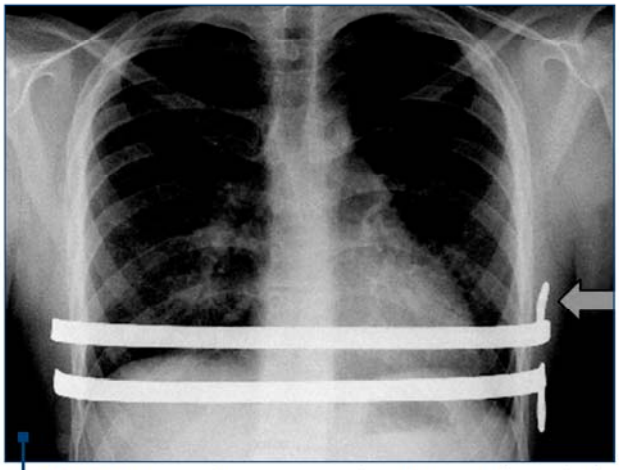

Figure 6. *Two single piece pectus bars (PSI® – Hofer medical, Fürstenfeld, Austria), showing an adjustment on the area of the upper stabilizer – wing (arrow)*

Indications for surgical correction are the following:

- Progression of the deformity despite physical measures (a Vertebral Index exceeding 25 or a Haller index greater than 3.25)
- A functional disorder of the heart in conjunction with arrhythmia or tachycardia disproportionate to exertion
- A marked and disturbing limitation of endurance capacity
- Pain in the pectus excavatum region
- Increasing psychological stress.

The modified minimally invasive pectus repair (MMIPR)

The original minimally invasive procedure described by Nuss in 1998, involving implantation of an individually produced bar without cartilage resection, has produced well to excellent cosmetic results **(Figure 3)**.

From 2006 on we use the single-piece implant with the integrated stabilizer wing (PSI® by Hofer Medical Austria) **(Figure 4 and Figure 6)**, which prevents metal abrasion and metal pollution of the body **(Figure 5)**[41]. Metal debris may induce a massive release of cytokines from inflammatory cells, causing local inflammatory reaction as well as widespread dissemination of metal debris[42, 43]. Surgical wire fixation, which is used in multiple-piece implants and involves the risk of breakage, is rendered unnecessary. The asymmetrical stabilizer flap permits implantation of two pectus bars without the risk of contact between the stabilizer flaps. This also reduces metal contact and metal abrasion. In contrast to the previously used pectus bar implants, the single-piece implant can be individually adjusted until the end of the pectus bar and thus achieves a perfect fit. Further advantages of the single-piece implant with an integrated asymmetrical slim stabilizer include easier handling and fewer complications.

In all modified minimally invasive pectus repair procedures (MMIPR), we perform an additional subxiphoidal incision for dissection of anterior mediastinal fibrous adhesions and safe preparation[44]. Through a small vertical epigastric incision about 3 cm in length, the distal sternum is separated from the anterior portion of the mediastinum, if necessary by transecting coarse connective tissue fibers, which may also be involved in the pathogenesis of the funnel chest.

Through the subxiphoidal epigastric incision we perform a mediastino-thoracic endoscopy and check the condition of the anterior thoracic wall as well as prepare the implant bed for the surgical procedure **(Figure 7)**.

Two small oblique skin incisions, just a few centimeters in size, are made close to the medioaxillary line. Via these incisions an individually bent single-piece metal bar (PSI® Hofer Medical, Austria) is implanted by crossing the intercostal spaces. The implanted bar is positioned at or near the deepest point of the funnel. The sites where the bar passes through the intercostal space must be exactly selected; they should lie close, but medial, to the funnel edge. Intraoperatively the sternum is elevated using a doubly supported Rochard retractor for safe preparation and better positioning of the individually c-shaped pectus bar, thus avoiding intercostal muscle stripping. The pectus bar is positioned by the use of special rotation instruments (Hofer Medical®, Austria) on both ends **(Figure 8)**. This surgical procedure is also useful in that it avoids intercostal muscle stripping.

The ends of the pectus bar are routinely covered by the partly mobilized anterior portion of the latissimus dorsi muscle. By using non-absorbable sutures (2/0 polyester suture/ Etibond®/Ethicon/Johnson & Johnson), the mobilized *latissimus dorsi* muscle is surgically reaffixed to the thoracic wall. Occasionally the bar has to be placed under the pectoralis major muscle. To strengthen the implant bed, the bar should be placed on the serratus anterior muscle. When performing pectus excavatum repair in older patients, during or after puberty, two pectus bars are used to reduce the physical load.

The metal pectus bar implant elevates the sternum and forces the rib cage back to its normal growth for a period of 2 to 3 years. During removal of the implant, the lateral skin scars are surgically reopened and the end of the implant without the stabilizer wing is bent straight.

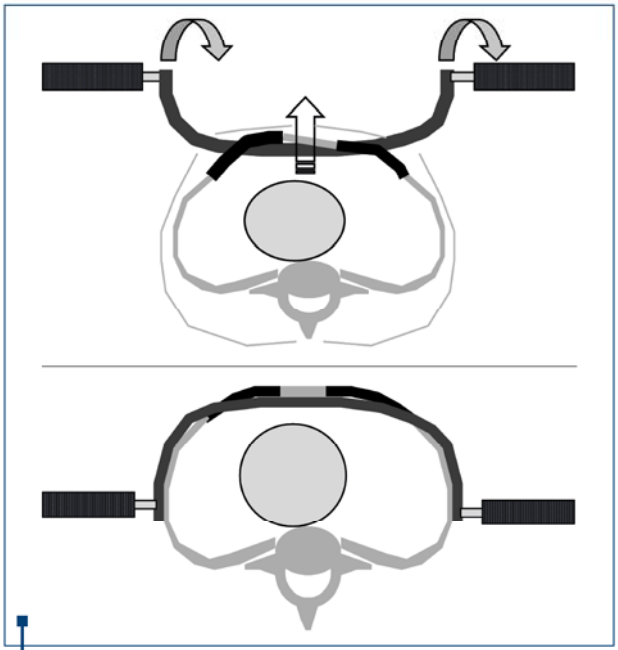

Figure 7-8. *The implant is taken synchronously on both sides with a special gripping tool and rotated*

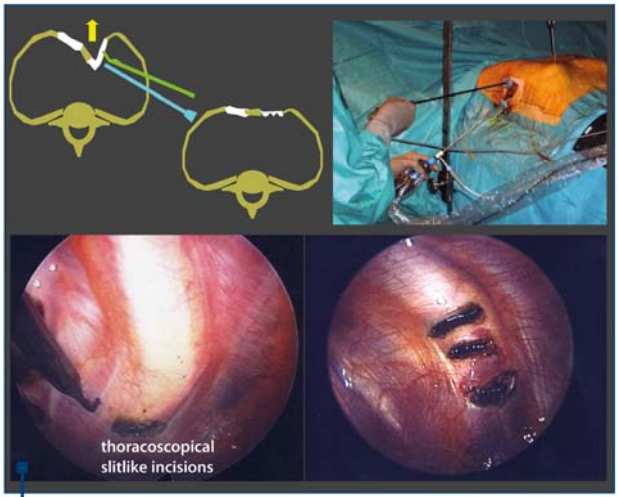

Figure 9. *Slit chondrotomies using hook electrocautery, performed under thoracoscopic guidance*

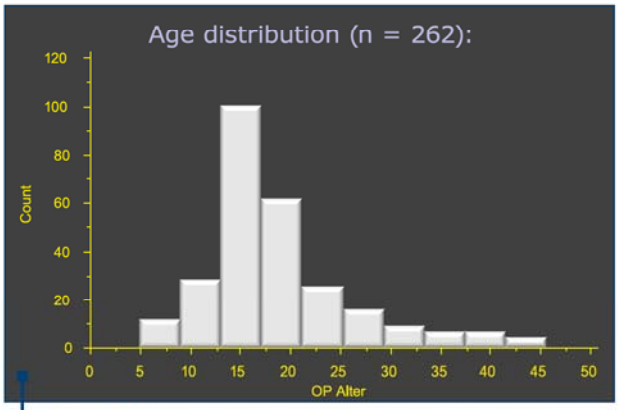

Figure 10. *Age distribution of 262 patients at the time of surgery*

The modified extended minimally invasive pectus repair (MEMIPR)

Especially in older patients with a stiff thorax, a curved sternum, severe asymmetrical forms or a mixed pigeon/funnel chest, the MIPR must be supplemented by additional surgical measures. The principal extended modifications are the following:

(1) In cases of a higher-grade or asymmetrical funnel chest, additional thoracoscopic chondrotomies **(Rokitansky method, Figure 9)** of the cartilaginous parts of the affected ribs via the lateral thoracic incisions have been extremely beneficial to the patient. Using hook electrocautery, a partial superficial slit dissection is performed in the cartilaginous portion of the ribs, in the region of posterior angulation. This step produces good cosmetic results even in higher-grade funnel chests[45].

(2) In recurrent deformities **(Figure 2)** with ossifications in the cartilaginous portion of the rib, slit-rib osteotomies via an additional skin incision are required to improve funnel flexibility.

(3) A further technical benefit is achieved by the wedge-shaped partial sternal osteotomy in cases of sternal rotation or curving. Patients with excessive curving of the sternum or rotational malpositioning may require a horizontal or an oblique wedge-shaped partial sternal osteotomy.

(4) Ultrasound-guided instillation of Macrolane® may be performed in patients with persistent minor deformities after correction. Macrolane® is a stabilized hyaluronic acid-based gel of non-animal origin (NASHA-based gel) and is well established for use in aesthetic facial procedures.

(5) In so-called combined forms, such as combined chicken and funnel chest, we perform partial rib resection as described by Ravitch-Welsh in addition to minimally invasive bar implantation. Protruded cartilaginous portions of the rib are peeled out of the perichondrium and removed[46].

Adequate pain relief, especially during the first three postoperative days, is achieved by bolus injection of piritramide (Dipidolor®) at a dose of 0.01-0.02 mg/kg BW. The patient doses the substance individually through a patient-controlled analgesia pump. Alternatively one may administer analgesia via an epidural catheter[47]. For adolescents undergoing minimally invasive pectus excavatum repair, thoracic epidural analgesia has proven superior to intravenous patient-controlled analgesia postoperatively as it resulted in lower postoperative pain scores and greater well-being[48].

Results

At our institution 262 patients (mean age: 17.7±7 years; 215 male and 47 female patients) could be analyzed after surgical pectus excavatum repair. The majority of the patients were between 14 and 20 years of age. We achieved successful correction in 6 patients aged older than 40 years (the oldest patient was a 45-year-old woman). Seven patients (mean age: 20±9 years) demonstrated a recurrence of funnel chest: 6 of them had undergone several alternative correction methods while 1 (age, 11 years) had undergone a typical MIPR. In 103 patients the pectus bar implant was left in the chest for a period of 1.4 to 6.5 years (mean: 3.4 years).

Table I List of the complications

Complications	MMIPR group (n= 121)	MEMIPR group (n= 141)
bar movement	4.9 %	1.6%
bar dislocation (op)	-	-
stabilizer dislocation (single piece bar)	2.3% (-)	- (-)
sc. infection	0.7%	0.8%
Pneumothorax >1cm apikal	1.4%	2.4%
pleural effusion (needs drainage)	2.1%	1.7%
sc. hematoma	1.7%	4.1%
tissue necrosis (single bar, without sternotomy)	2.5%	-
liver perforation	-	-
heart perforation	-	-

No restriction of sports was required. One male patient (21 years) with two single-piece pectus bar implants participated in the "ironman competition" (3.8 km of swimming, 180 km of cycling, and 42.195 km of running).

Modified minimally invasive pectus repair (MMIPR) was performed in 121 patients (age: 15.2±5 years; 74% symmetrical pectus excavatum). Most of the patients received one pectus bar; 13.2% received two bars. Modified extended minimally invasive pectus repair (MEMIPR) using the additional surgical techniques mentioned above was performed in 141 patients (mean age: 22.5±8 years; symmetrical pectus excavatum in 57.4%; carinatum/excavatum in 4.9%). Two pectus bars had to be used in 58.1% of cases. Rib chondrotomy under thoracoscopic guidance (Rokitansky method) was used in 48% of patients (mean age: 20.2±7 years) to enhance funnel flexibility[45]. The quantity of Macrolane® administered in the eight patients ranged between 5 and 20 cc. **Figure 11** shows the distribution of modified extended surgical techniques as well as the mean age of patients in the corresponding group.

The benefit of the operation was demonstrated by a reduction of the vertebral index (VI) as measured on chest X-rays preoperatively, postoperatively, and several years (mean: 3.4 years) after explanation of the implants. **Figure 12** illustrates the significant improvement in the vertebral index. Blue bars refer to the group that underwent modified minimally invasive pectus repair (MMIPR); yellow bars show the results in those who underwent extended minimally invasive pectus repair (MEMIPR). In both groups the pathologically increased vertebral index fell to a physiological range. Recurrences were observed in 0.9% of patients. In one case we removed the pectus bar before the spurt of pubertal growth (the first pectus bar was explanted at the age of 14 years); the resulting funnel chest recurrence had to be corrected a second time.

Thoracoscopic chondrotomies resulted in an excessively flexible thorax in 4% of patients (particularly younger ones), who developed a slight pectus carinatum which disappeared after removal of the metal pectus bars. Following explantation of the implants, the patients were asked to assess the cosmetic outcome of the operation. The operation was rated either good or excellent by 95%.

Intraoperative and postoperative complications in the two groups are shown in **Table I**. No life-threatening complications or deaths have been registered thus far. Bar movement in patients who underwent additional measures (MEMIPR) was lower than that in the MMIPR group. Subcutaneous hematoma occurred more frequently in patients who underwent additional measures. No re-thoracotomy was required in the 262 patients who underwent MMIPR or MEMIPR.

A patient-controlled analgesia pump was used in 80% of cases. The remaining patients opted for analgesic drugs via an epidural catheter. No complications occurred during pectus bar removal.

Discussion

The procedure of minimally invasive pectus repair (MIPR) described by Donald Nuss remains the "gold standard" for pectus excavatum correction[40]. The principal indications for surgery include progression of the deformity, cardiac and respiratory morbidity, and psychological impairment. Significant improvements of cardiac and respiratory function have been reported after pectus excavatum repair[24, 25, 38, 49-51]. In addition to postoperative enlargement of thoracic lung cavities in severe deformities, the reduction of cardiac compression appears to be an important aspect.

Donald Nuss mentioned 6 years as the optimum age for surgery because the chest is still soft and elastic at this age[40]. Today the median age for surgery is around 14 years[9]. Given the growth of lungs until the age of 9 years and the intensive growth spurt of the chest during puberty, the best age for correction is marked by two peaks: the first is between the age of 6 and 8 years, depending on the severity of the condition, while the second is between the age of 14 and 17 years[52, 53].

We use the original single-piece implant with the integrated stabilizer wing (PSI® by Hofer Medical/ Fürstenfeld/ Austria) because it prevents metal abrasion caused by friction between the components of multiple-piece pectus bar systems. Metal debris may induce a massive release of cytokines from inflammatory cells[43]. Surgical wire fixation, as used in multiple-piece implants, bears the risk of breakage and is no longer required. The asymmetric stabilizer flap permits implantation of two pectus bars with no risk of contact between the stabilizer flaps. This also reduces metal contact and metal abrasion.

However, in cases of the elderly patients (adults) with a stiff thorax, a curved sternum, severe asymmetrical forms or a mixed pigeon/funnel chest, MIPR has to be supplemented by additional surgical measures.

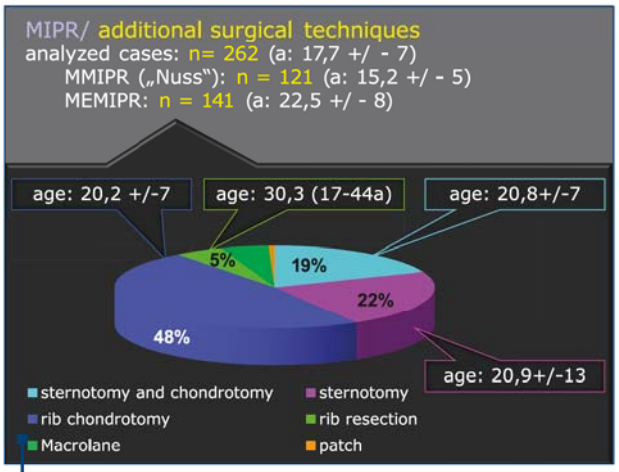

Figure 11. *Additional surgical measures in MEMIPR (with the patients' mean ages)*

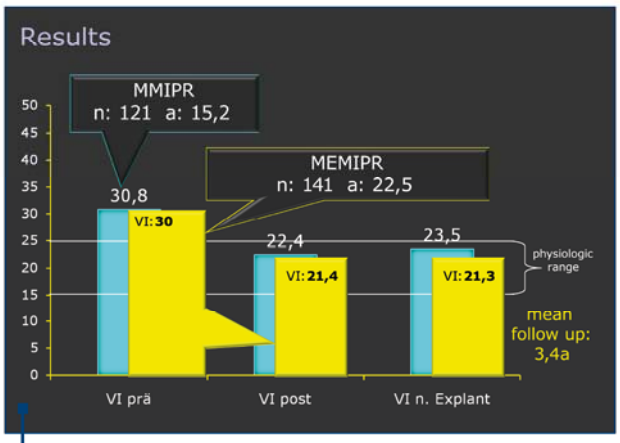

Figure 12. *Vertebral index (VI) in the pre- and postoperative period as well as after the pectus bar explantation (after a mean of 3.4*

In order to perform surgery safe and successfully as well as reduce postoperative complications, MIPR was modified significantly (MMIPR) in terms of additional subxiphoidal incision, anterior mediastinal-mediastinoscopic mobilization, equalization of the funnel during pectus bar placement, and fixation of the implant ends in a bag of the *latissimus dorsi* muscle. Pericardial lesions and perforations of the heart or liver must be avoided. As the pericardium is much thicker than the pleura, injury to the pericardium can be avoided by careful undermining[54]. We modified the minimally invasive method of repair (MMIRP) by performing an additional small epigastric-subxiphoid incision, and were thus able to mobilize the anterior mediastinum from the sternum and monitor the procedure in this area during surgical preparation by endoscopy. In severe forms of the condition or in patients with a history of cardiorespiratory problems, Felts et al. have also recommended a short subxiphoid incision to release pleural and pericardial adhesions[44]. The cosmetic flaw of a small scar in the upper abdomen should be accepted in view of the safety of the procedure. In our minimally invasive repair procedures we encountered no severe complications such as cardiac or liver perforation[55]. Due to controlled anterior mediastinal mobilization as well as the straightening of the pectus bar end during removal, vascular and cardiac injuries may be ruled out significantly; perhaps also the late onset hemorrhages[54-56].

Modified minimally invasive pectus repair (MMIPR) was performed in 121 patients (mean age: 15.2±5 years; 74% symmetrical). The majority of patients received one pectus bar; 13.2% received two bars. Modified extended minimally invasive pectus repair (MEMIPR) using the additional surgical techniques mentioned above was performed in 141 patients (mean age: 22.5±8 years; 57.4% symmetrical; 4.9% carinatum/excavatum). Six patients older than 40 years of age were also treated successfully. MIPR has been rarely reported in patients of this age[57-59]. However, in our experience simple MIPR without additional surgical measures (MEMIPR) does not yield the desired results.

Two pectus bars had to be used in 58.1% of cases. The use of two pectus bars reduces pressure at the sternum, especially in those areas where the bar crosses the ribs by doubling the bearing surfaces. Aseptic tissue necrosis in the areas of support has not been observed ever since we started to implant two bars in selected patients. The advantages of using two pectus bars have been described elsewhere[60]. Implantation of three pectus bars was deemed unnecessary in our patients[9].

In some certain cases the modified technique (MEMIPR) had to be supplemented by additional surgical measures such as partial sternotomy (23%), slit-rib chondrotomy under thoracoscopic guidance (48%; mean age: 20.2±7 years; Rokitansky method), rib resection (5%), and occasionally rib osteotomy[45]. The pressure on contact areas between the pectus bar and ribs or the sternum can again be reduced by this step. We observed no "pressure-related aseptic tissue necrosis" when we used two bars and/or performed our MEMIPR method.

A Macrolane® injection (5-20 cc) was administered in patients with residual minor deformities. We employed a fan-shaped injection technique with small injection depots (ranging to 5 cc), using ultrasound guidance intraoperatively.

Bar displacement, which has been reported to occur in at least 1% of patients in the published literature, was not encountered in any of our 262 patients[9]. Minor bar movements occurred in 4.9% in the MMIPR group, and just 1.6% in the MEMIPR group. Recurrence was seen in a mere 0.9% of 103 patients who underwent bar explantation, after a mean period of 3.4 years. In one exemplary case we removed the pectus bar too early, i.e. prior to the period of intensive pubertal growth. The first pectus bar was explanted at the age of 14 years. This patient required surgical correction of a recurrent funnel chest.

Modifications (MMIPR and MEMIPR) of the original MIPR procedure, including the single-piece pectus bar implant, yielded very satisfactory results especially in older patients with severe deformities and funnel chest recurrence. ■

References

1. Fokin AA, Steuerwald NM, Ahrens WA, Allen KE. Anatomical, histologic, and genetic characteristics of congenital chest wall deformities. Seminars in thoracic and cardiovascular surgery. 2009 *Spring*; 21(1):44-57.
2. Fonkalsrud EW. 912 open pectus excavatum repairs: changing trends, lessons learned: one surgeon's experience. *World journal of surgery.* 2009 Feb; 33(2):180-90.
3. Creswick HA, Stacey MW, Kelly RE, Jr., Gustin T, Nuss D, Harvey H, et al. Family study of the inheritance of pectus excavatum. *Journal of pediatric surgery.* 2006 Oct; 41(10):1699-703.
4. Shamberger RC, Welch KJ. Surgical repair of pectus excavatum. *Journal of pediatric surgery.* 1988 Jul; 23(7):615-22.
5. Leung AK, Hoo JJ. Familial congenital funnel chest. *American journal of medical genetics.* 1987 Apr; 26(4):887-90.
6. Kotzot D, Schwabegger AH. Etiology of chest wall deformities--a genetic review for the treating physician. *Journal of pediatric surgery.* 2009 Oct; 44(10):2004-11.
7. Dietz HC, Ramirez F, Sakai LY. Marfan's syndrome and other microfibrillar diseases. *Adv Hum Genet.* 1994; 22:153-86.
8. Kelly RE, Jr., Shamberger RC, Mellins RB, Mitchell KK, Lawson ML, Oldham K, et al. Prospective multicenter study of surgical correction of pectus excavatum: design, perioperative complications, pain, and baseline pulmonary function facilitated by internet-based data collection. *Journal of the American College of Surgeons.* 2007 Aug; 205(2):205-16.
9. Kelly RE, Goretsky MJ, Obermeyer R, Kuhn MA, Redlinger R, Haney TS, et al. Twenty-one years of experience with minimally invasive repair of pectus excavatum by the Nuss procedure in 1215 patients. *Annals of surgery.* 2010 Dec; 252(6):1072-81.
10. Sukumaran TU, Manjooran RJ, Thomas K. A clinical profile of mitral valve prolapse syndrome. *Indian journal of pediatrics.* 1990 Nov-Dec; 57(6):771-3.
11. Park JM, Varma SK. Pectus excavatum in children: diagnostic significance for mitral valve prolapse. Indian journal of pediatrics. 1990 Mar-Apr; 57(2):219-22.
12. Garusi GF, D EA. Angiocardiographic Patterns in Funnel-Chest. *Cardiologia.* 1964; 45:313-30.
13. Blickman JG, Rosen PR, Welch KJ. Pectus excavatum in children: Pulmonary scintigraphy before and after corrective surgery. Radiology. 1985; 156:781-2.
14. Cahill JL, Lees GM, Robertson HT. A summary of preoperative and postopertive cardiorespiratory performance in patients undergoing pectus excavatum and carinatum repair. *J Pediatr Surg.* 1984; 19:430-3.
15. Nuss D. Minimally invasive surgical repair of pectus excavatum. Seminars in pediatric surgery. 2008 Aug; 17(3):209-17.
16. Lawson ML, Mellins RB, Paulson JF, Shamberger RC, Oldham K, Azizkhan RG, et al. Increasing severity of pectus excavatum is associated with reduced pulmonary function. *The Journal of pediatrics.* 2011 Aug; 159(2):256-61 e2.
17. Rehbein F, Wernicke HH. The operative treatment of the funnel chest. *Arch Dis Child.* 1957; 32:5-11.
18. Szydlik S, Jankowska-Szydlik J, Kasprzyk M, Dyszkiewicz W, Adamczak J, Zwarun D. An effect of nuss procedure on lung function among patients with pectus excavatum. *Polski przeglad chirurgiczny.* 2013 Jan 1; 85(1):1-5.
19. Neviere R, Benhamed L, Duva Pentiah A, Wurtz A. Pectus excavatum repair improves respiratory pump efficacy and cardiovascular function at exercise. The *Journal of thoracic and cardiovascular surgery.* 2013 Feb; 145(2):605-6.
20. Chen Z, Amos EB, Luo H, Su C, Zhong B, Zou J, et al. Comparative pulmonary functional recovery after Nuss and Ravitch procedures for pectus excavatum repair: a meta-analysis. *Journal of cardiothoracic surgery.* 2012; 7:101.
21. Mocchegiani R, Badano L, Lestuzzi C, Nicolosi GL, Zanuttini D. Relation of right ventricular morphology and function in pectus excavatum to the severity of the chest wall deformity. The American journal of cardiology. 1995 Nov 1; 76(12):941-6.
22. Kowalewski J, Brocki M, Dryjanski T, Zolynski K, Koktysz R. Pectus excavatum: increase of right ventricular systolic, diastolic, and stroke volumes after surgical repair. *The Journal of thoracic and cardiovascular surgery.* 1999 Jul; 118(1):87-92; discussion -3.
23. Andres AM, Hernandez F, Martinez L, Fernandez A, Encinas JL, Avila LF, et al. [Cardiac function alterations in pectus excavatum]. Chirugia pediatrica: organo oficial de la Sociedad Espanola de Cirugia Pediatrica. 2005 Oct; 18(4):192-5.
24. Krueger T, Chassot PG, Christodoulou M, Cheng C, Ris HB, Magnusson L. Cardiac function assessed by transesophageal echocardiography during pectus excavatum repair. *The Annals of thoracic surgery.* 2010 Jan; 89(1):240-3.
25. Sigalet DL, Montgomery M, Harder J, Wong V, Kravarusic D, Alassiri A. Long term cardiopulmonary effects of closed repair of pectus excavatum. *Pediatric surgery international.* 2007 May; 23(5):493-7.
26. Sigalet DL, Montgomery M, Harder J. Cardiopulmonary effects of closed repair of pectus excavatum. *Journal of pediatric surgery.* 2003 Mar; 38(3):380-5; discussion-5.
27. Neviere R, Pentiah AD, Montaigne D, Wurtz A. Pectus excavatum repair improves cardiovascular function at maximal exercise by facilitating heart filling. European journal of cardio-thoracic surgery : official journal of the European Association for Cardio-thoracic Surgery. 2013 Mar; 43(3):661.
28. Malek MH, Berger DE, Housh TJ, Marelich WD, Coburn JW, Beck TW. Cardiovascular function following surgical repair of pectus excavatum: a metaanalysis. *Chest.* 2006 Aug; 130(2):506-16.
29. Tang M, Nielsen HH, Lesbo M, Frokiaer J, Maagaard M, Pilegaard HK, et al. Improved cardiopulmonary exercise function after modified Nuss operation for pectus excavatum. European journal of cardio-thoracic surgery : official journal of the European Association for Cardio-thoracic Surgery. 2012 May; 41(5):1063-7.
30. Hadolt B, Wallisch A, Egger JW, Hollwarth ME. Body-image, self-concept and mental exposure in patients with pectus excavatum. *Pediatric surgery international.* 2011 Jun; 27(6):665-70.
31. Steinmann C, Krille S, Mueller A, Weber P, Reingruber B, Martin A. Pectus excavatum and pectus carinatum patients suffer from lower quality of life and impaired body image: a control group comparison of psychological characteristics prior to surgical correction. *Eur J Cardiothorac Surg.* 2011 Nov; 40(5):1138-45.
32. Marcovici PA, LoSasso BE, Kruk P, Dwek JR. MRI for the evaluation of pectus excavatum. *Pediatric radiology.* 2011 Jun; 41(6):757-8.
33. Raichura N, Entwisle J, Leverment J, Beardsmore CS. Breath-hold MRI in evaluating patients with pectus excavatum. *The British journal of radiology.* 2001 Aug; 74(884):701-8.
34. Calloway EH, Chhotani AN, Lee YZ, Phillips JD. Three-dimensional computed tomography for evaluation and management of children with complex chest wall anomalies: useful information or just pretty pictures? *Journal of pediatric surgery.* 2011 Apr; 46(4):640-7.
35. Haller JA, Kramer S, Lietman SA. Use of CT Scans in Selection of Patients for Pectus excavatum Surgery: A preliminary Report. *J Pediatr Surg.* 1987; 22(904):906.
36. Kilda A, Lukosevicius S, Barauskas V, Jankauskaite Z, Basevicius A. Radiological changes after Nuss operation for pectus excavatum. *Medicina.* 2009; 45(9):699-705.
37. Kilda A, Basevicius A, Barauskas V, Lukosevicius S, Ragaisis D. Radiological assessment of children with pectus excavatum. *Indian journal of pediatrics.* 2007 Feb; 74(2):143-7.
38. Morshuis WJ. Pectus excavatum: A clinical Study with a Long - Term postoperative Follow - Up. *Eur J Cardio-thorac Surg.* 1992;6:318-23.
39. Nuss D, Croitoru DP, Kelly RE, Jr., Goretsky MJ, Nuss KJ, Gustin TS. Review and discussion of the complications of minimally invasive pectus excavatum repair. European journal of pediatric surgery : official journal of Austrian Association of Pediatric Surgery [et al] = *Zeitschrift fur Kinderchirurgie.* 2002 Aug; 12(4):230-4.
40. Nuss D, Kelly RE, Jr., Croitoru DP, Katz ME. A 10-year review of a minimally invasive technique for the correction of pectus excavatum. *Journal of pediatric surgery.* 1998 Apr; 33(4):545-52.
41. Cundy TP, Kirby CP. Serum metal levels after minimally invasive repair of pectus excavatum. *Journal of pediatric surgery.* 2012 Aug; 47(8):1506-11.
42. Case CP, Langkamer VG, James C, Palmer MR, Kemp AJ, Heap PF, et al. Widespread dissemination of metal debris from implants. The Journal of bone and joint surgery British volume. 1994 Sep; 76(5):701-12.
43. Schiavone Panni A, Vasso M, Cerciello S, Maccauro G. Metallosis following knee arthroplasty: a histological and immunohistochemical study. *Int J Immunopathol Pharmacol.* 2011 Jul-Sep; 24(3):711-9.
44. Felts E, Jouve JL, Blondel B, Launay F, Lacroix F, Bollini G. Child pectus excavatum: correction by minimally invasive surgery. Orthopaedics & traumatology, surgery & research : *OTSR.* 2009 May; 95(3):190-5.
45. Rokitansky A. Thorax. In: Zachariou Z, ed. Pediatric Surgery Digest: Springer-Verlag Berlin Heidelberg, 2009:227 - 303.
46. Ravitch MM. The Operative Treatment of Pectus Excavatum. *Annals of surgery.* 1949 Apr; 129(4):429-44.
47. Soliman IE, Apuya JS, Fertal KM, Simpson PM, Tobias JD. Intravenous versus epidural analgesia after surgical repair of pectus excavatum. *American journal of therapeutics.* 2009 Sep-Oct; 16(5):398-403.
48. Weber T, Matzl J, Rokitansky A, Klimscha W, Neumann K, Deusch E. Superior postoperative pain relief with thoracic epidural analgesia versus intravenous patient-controlled analgesia after minimally invasive pectus excavatum repair. *The Journal of thoracic and cardiovascular surgery.* 2007 Oct; 134(4):865-70.
49. Coln E. Demonstrating relief of cardiac compression with the Nuss minimally invasive repair for pectus excavatum. 2006.
50. Neviere R, Montaigne D, Benhamed L, Catto M, Edme JL, Matran R, et al. Cardiopulmonary response following surgical repair of pectus excavatum in adult patients. European journal of cardio-thoracic surgery : official journal of the European Association for Cardio-thoracic Surgery. 2011 Aug; 40(2):e77-82.
51. Lawson ML, Mellins RB, Tabangin M, Kelly RE, Jr., Croitoru DP, Goretsky MJ, et al. Impact of pectus excavatum on pulmonary function before and after repair with the Nuss procedure. *Journal of pediatric surgery.* 2005 Jan; 40(1):174-80.
52. Smeets M, Brunekreef B, Dijkstra L, Houthuijs D. Lung growth of pre-adolescent children. The European respiratory journal : official journal of the European Society for Clinical Respiratory Physiology. 1990 Jan; 3(1):91-6.
53. Zeltner TB, Caduff JH, Gehr P, Pfenninger J, Burri PH. The postnatal development and growth of the human lung. I. Morphometry. *Respir Physiol.* 1987 Mar; 67(3):247-67.
54. Nagasao T, Takayama M, Miyamoto J, Ding W, Jiang H. Anatomical study of the thorax for the safe performance of the Nuss procedure for pectus excavatum. *The Thoracic and cardiovascular surgeon.* 2011 Feb; 59(1):34-9.
55. Hoel TN, Rein KA, Svennevig JL. A life-threatening complication of the Nuss procedure for pectus excavatum. *The Annals of thoracic surgery.* 2006 Jan; 81(1):370-2.
56. Jemielity M, Pawlak K, Piwkowski C, Dyszkiewicz W. Life-threatening aortic hemorrhage during pectus bar removal. *The Annals of thoracic surgery.* 2011 Feb; 91(2):593-5.
57. Esteves E, Paiva KC, Calcagno-Silva M, Chagas CC, Barbosa-Filho H. Treatment of pectus excavatum in patients over 20 years of age. Journal of laparoendoscopic & advanced surgical techniques Part A. 2011 Jan-Feb; 21(1):93-6.
58. 58. Olbrecht VA, Arnold MA, Nabaweesi R, Chang DC, McIltrot KH, Abdullah F, et al. Lorenz bar repair of pectus excavatum in the adult population: should it be done? The Annals of thoracic surgery. 2008 Aug; 86(2):402-8; discussion 8-9.
59. 59. Pilegaard HK. Extending the use of Nuss procedure in patients older than 30 years. European journal of cardio-thoracic surgery : official journal of the European Association for Cardio-thoracic Surgery. 2011 Aug; 40(2):334-7.
60. 60. Nagaso T, Miyamoto J, Kokaji K, Yozu R, Jiang H, Jin H, et al. Double-bar application decreases postoperative pain after the Nuss procedure. The Journal of thoracic and cardiovascular surgery. 2010 Jul; 140(1):39-44, e1-2.