III. PEDIATRIC SURGERY

EVOLVING SURGICAL TECHNIQUES FOR PECTUS EXCAVATUM CORRECTION

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Abstract
The principles of the surgical treatment for pectus excavatum were established more than 50 years ago, still new treatment techniques and methods are being developed at the present time. Many different materials have been used by orthopedic surgeons for the repair of this thoracic deformity. The present study is a review of both old and new techniques that were designed for a better surgical correction of pectus excavatum.

Keyword : pectus excavatum, surgical procedures, chest deformity.

It is the most common malformation of the thorax, usually diagnosed soon after birth [18].

The first case report of pectus excavatum was made by Bauhinus [19] in 1494, who described the congenital deformity in a seven years old child. Since the beginning of the century, many authors described in detail the anatomy, pathophisiology and the treatment of P.E. [20]

The main characteristic of this deformity is a depression of the anterior wall of the thorax.

P.E. occurs in 86% of cases after the first year of life. It is three times more frequent in boys than girls. 15% of patients have scoliosis and 11% have a family history of thorax malformation. The deformity can be symmetric or asymmetric. Seldom it is associated with Marfan syndrome. [23] There are several theories regarding the aetiology of P.E.:

- the theory of the fibrous sternal-vertebrous ligament of Bauhinus;
- the theory of secondary hypoplasia and atrophy of the sternal-diafragmatic muscles postulated by Brokin;
- the theory of costal dyscondroplasia, which nowadays is most accepted, according to which the deformity of the sternum in P.E. or pectus carinatum occurs due to an excessive growth of the costal cartilages.

In 1913, Sauerbruh performed the first surgical procedure and was followed by many others who managed to improve the technique, so that nowadays postoperative results are almost perfect. [4] Surgical intervention indications are:

A. **Age** - experience shows that the procedure can be performed safely in children. The younger the patient, the easier the recovery. This is why surgery is indicated whenever the deformity is severe or progressive. In children, persistence of sternum depression during forced exhalation is as important as the depth of depression or paradoxical movements of the xyphoid [23]. According to many surgeons, the appropriate age for intervention is between 2-6 years, though controversies still exist.

In a study including 12 patients aged under 4 with P.E. who underwent surgery, Haller evaluates complications due to thorax development. Results mention that growth failure of the thorax is the consequence of resection of costal growth center [27]. The author of this article emphasised on the need of delaying surgical correction till the age of 6-8. The younger the patient, the smaller the resectionof the chest wall should be. Five patients out of twelve had to accept reintervention for expansion of thorax cage because of developmental failure [27]. Examining the results related to age at operation, several things are clear : the younger the patient at the time of correction, provided he is at least 3 years of age, the better his chances are for an excellent cosmetic result. (Sbokos et al.) [24] The optimum age for correction of P.E. seems to be between 6 and 10 years of age. If the patient is younger than 3 or older than 20 he has less chance of an excellent result. The tendencies are to operate on patients at the extremes of age more for relief of symptoms than in the hope of an excellent cosmetic result. [24] Results obtained in a study including 72 patients are shown in the following table:

Age	Number	Excellent	Good	Poor
<3	6	2	2	2
3-5	17	15	1	1

6-10	23	23	0	0
11-20	21	12	6	3
>20	5	1	3	1
Total	72	53	12	7

Table 1. Age at correction/ long term results relationship [28].

The problem of optimum age for intervention remains controversial, different authors sustaining different opinions:

- Haller obtained good results at different groups of age; 85-90 % are good or very good in children younger than 5 and older than 15;
- Skobos has the best results in children aged between 6 and 10 and the worst in subjects aged under 3 or over 20;
- Von der Oelnitz has the worst results in children aged between 3 and 5, respectively 9 and 12, suggesting optimum age for intervention over 12.

B. **Depression severity**

- Swenson indicates surgery when sternum depression exceeds 3 cm; between 2-2.5 cm depth the patient should be reevaluated in a year; less than 2 cm - there is no need for intervention.
- Haller indicates surgery if pectus index exceeds 3.25.
- Coexistence with other malformation demands a precise diagnosis, followed by deciding the need of surgery and the order of priorities.

Surgical management of chest wall deformities begins around 1911, when Meyer and Sauerbuch first attempt the correction of P.E. In 1929, Brown, Ochner and DeBakey recommend fixation of sternum after surgery by external traction (Jacobs` frame). In 1945 Lester and Ravitch suggest radical resection of costochondral cartilages, as well as a posterior transverse sternotomy. The sternum was fixed by lifting it to the level of the second costochondral cartilage. In 1958 Welch recommends that the whole perichondrium be left in place, sternum osteotomy without fixing it with metal plate. To avoid postoperative recurrences, surgeons use several methods to maintain the sternal bone in place (metal plates, Kirschner wire, Steinman nails) [23]. Most of surgical techniques try to solve the cause of thorax deformities, that is the excessive growth of costochondral cartilage. In 1974, Haller fixes costal cartilages at the level of the second rib in overcorrected position, in order to avoid postoperative recurrences. Haller introduces the so-called tripod support cerated to sustain the sternum. This method is based on an oblique incision (condrotomy) on the normal ribs (the last pair of unmodified ribs), followed by overlapping of these segments on the normal ribs and suturing them.

In 1980, Japan, Wada [59] presented his technique called " sternoturnover", in which the sternum was used among large numbers of patients as a 180° rotated free graft fastened to the costal cartilages. This technique was abandonned because of postoperative complications, the most undesireable being sternal bone necrosis. [59]

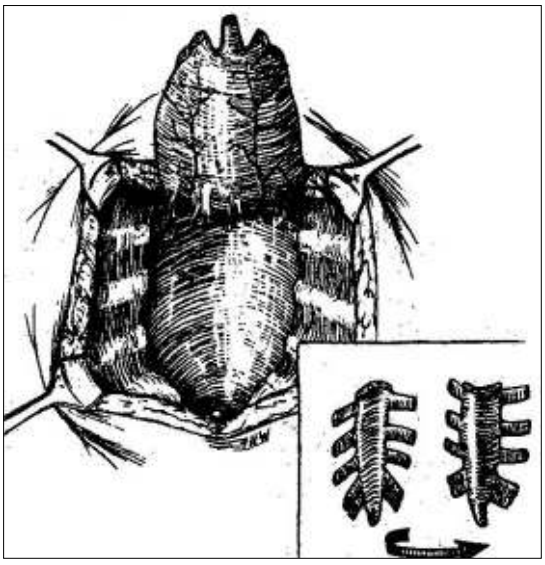


Fig. 1. Sternoturnover-Wada [59]

The so-called „sternoturnover" procedure performed by various surgeons turned out to have poor results, due to sternum and muscle necrosis. Taguchi [41] presents a modified „sternal turnover" technique; he maintains the bone's blood supply by keeping the internal mammary arteries on both sides. This procedure is mostly recommended to patients older than 15 years. The operative technique consists of :

- Vertical submammary incision is made in boys, transverse incision in girls;
- Dissection of pectoral muscles and exposure of skeletal chest wall;
- The rectus abdominis muscles are divided and the retrosternal space is prepared, thus creating a tunnel in the anterior mediastinum and separating at the same time the pleura from the anterior skeletal chest wall;

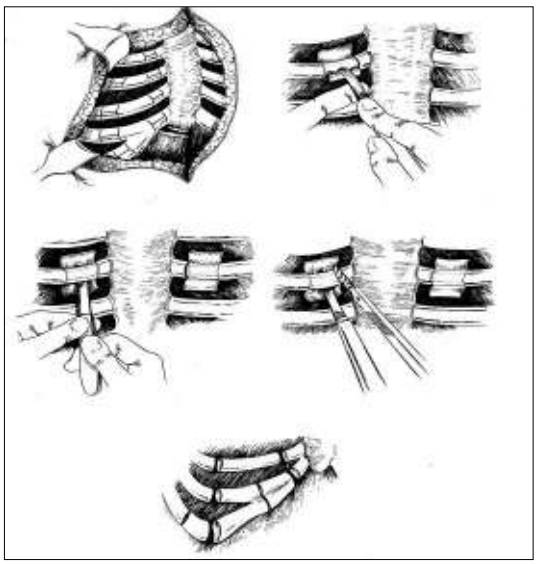
- From the first to the third ribs are divided bilaterally at their junction with the cartilage;
- The sternal bone is freed at the level of the third rib by a transverse sternotomy, keeping the internal mammary arteries;
- Internal mammary arteries are carefully prepared 5 cm cranially and 2 cm caudally ; the deformed sternum is turned 180° over, taking care not to section arteries; afterwards, the costal cartilage is fastened to the edge of the sternum with wire or dexon.

It must be emphasised on the importance of checking the blood supply after sternum turnover. Finally, the excess of bony tissue at the level of the sternum should be removed, otherwise the thorax would look like some kind of a pectus carinatum.

Eric Fonkalsrud published a study over 25 years including 252 patients who underwent surgery using Ravitch technique, modified by Welch and Haller [33]. The operative technique consists of :

- Submammary transverse incision ;
- Elevation of cutaneous flap from muscles, avoiding major bleeding by electrocoagulation;
- Pectoral muscles are dissected free from the sternum and costal cartilages are reflected sideways;
- The perichondrium is incised longitudinally, bilaterally on its anterior surface at the level of the last 4-5 costochondral cartilages; deformed cartilages are resected subperichondrially with the aid of an elevator;
- The xyphoid process is detached from the sternal bone;
- The perichondrium and intercostal muscles are resected medially to the internal mammary arteries;
- The retrosternal space is mobilized;
- The pleura is incised on the right and a drain tube is inserted;
- A transverse sternotomy is made at the level of the last normal rib;
- The posterior tabula externa of the sternum is fractured, without completely interrupting its blood supply, thus enabling to handle the sternal bone in desired position;
- The anterior sternotomy is sutured;
- In children aged under 5, the perichondrium from the 5th to the last rib is sutured on the midline;
- The xyphoid process and the perichondrium **teci** are reinserted;
- The pectoral and rectus abdominis muscles are sutured in normal position;
- The wound is closed in layers, and the drain is removed 3 days after surgery.

Average surgical time required in forty interventions was three hours and average time for hospital admision was about five days, during which antibiotics were given to patients. Attentive skin suture reduces the incidence of inaesthetic scars.



Picture 2. The surgical procedure [35]

Professor C. Coman from Romania describes another procedure for the management of P.E. [25]:

On one hand, midline incision is abandonned because of poor aesthetic results, thus avoiding delayed healing and scars. On the other hand, transverse incision is considerred insufficient to expose the interested area. Specific for this procedure are the two parasternal incisions made along the costal arch, leaving the sternum coverred and allowing at the same time removal of cartilages in good circumstances.

The main difficulty encounterred by the author is the failure of preserving the perichondrium.

Nevertheless, the following technique seems to offer better results:

-procedure starts with incision at the costochondral junction with the special mention that the perichondrium must be entirely left in place.

-at this level, the cartilage is severed up to the posterior perichondrium.

-cartilage is lifted and the posterior perichondrium is digitally dissected to its junction with the sternum.

-the cartilage is mobilized from its joint with the sternal bone, lifting its sternal end and thus freeing the anterior perichondrium. This technique allows preservation of the perichondrium, having a decisive role in postoperative results. Resection of xyphoid process is not cumpolsory, thus avoiding detachment of rectus abdominis muscles, which might lead to postoperative hypotonia. It ought to be mentioned that in case of a severe deformity where the xyphoid process complicates the correction, its resection must be carried out. Next, the retrosternal space is dissected by blunt finger dissection, starting at the resected cartilages. The sternum is mobilized and brought to overcorrected position by transverse pyramid-shaped sternotomy at the level of the second or third intercostal space. Sternum is supported by retrosternal stainless steel plates (C. Carpinisan et all.) In case of asymmetric deformities, the sustaining plate is obliquelly, medially and upwards oriented. Symmetric deformities, usually occuring in patients with increased longitudinal thorax diameter, are solved by inserting two parallel metal plates. Drain tubes are inserted in the retrosternal space and at the site condrectomy was performed.

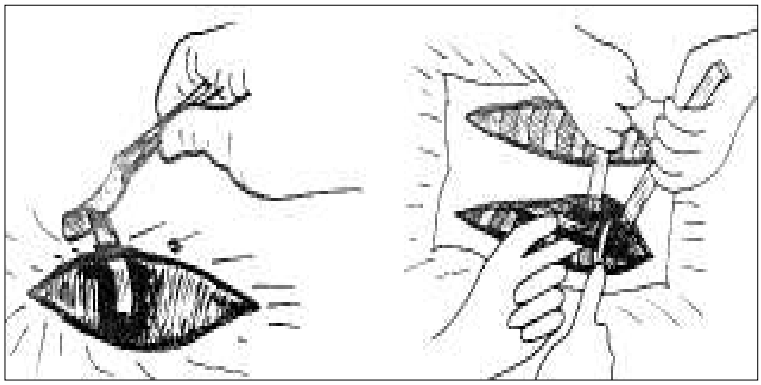


Fig.3 Coman technique [25]

Kobayashi describes a minimal invasive procedure for the management of P.E., coming up with a partial costal cartilage resection and sternal osteotomy, the entire intervention being carried out through a 2.5-4 cm skin incision. [37]

The incision is located just above the xyphoid process, the procedure being assisted by an thoracoscope.[37]

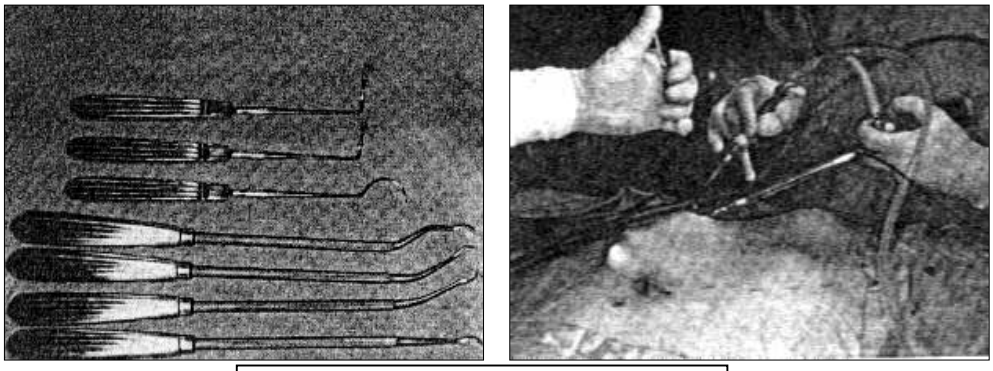


Fig 4 Instruments used by Kobayachi [37]

In addition, stab wounds of less than 3 mm in diameter are also made, in some cases, for insertion of the surgical instruments to facilitate the operation.The ribs and rib cartilages are exposed beyond the affected area through a prexyphoid incision under thoracoscopic control. The mobility of the skin incision site is thus enhanced, and it is possible to perform most of the subperichondrial partial costal cartilage resection under direct visualization. [37]

A retrosternal support is also used for keeping the sternum in desired position.The authors use specially designed curved perichondrial elevators for perichondrium resection.[37]

The pectoralis major muscle and the rectus abdominis muscle are incised where they attach to the sternum and ribs. Next, the subperichondrial space is prepared, followed by an oblique incision of the costal cartilages and removal of excess cartilages. [37]

The authors mention the difficulty of resecting the superior-most costal cartilages (third or fourth) due to the low location of the initial incision. [37]

The costal cartilage resection with the endoscope is facilitated by the use of a surgical arm that holds the endoscope. Finally, a wedge osteotomy of the sternum is performed at the point of maximum curve deformation of

the sternum. The deformed sternum is corrected manually by performing a green stick fracture at the osteotomy site. The elevated sternum is maintained by a strut that is inserted into the retrosternal space. Finally, the divided xyphoid process and muscle are sutured to their original point of attachment. Skin is closed in two layers, and two suction drains are inserted into the subcutaneous and prepleural space. The thoracic cage correction results obtained using this procedure were the same as those obtained using the conventional open method, except for the minimized operative scars. Specifically, the operative time was longer for those patients in whom subperichondrial dissection of the superior-most third or fourth rib cartilage was needed, given the fact that this area is hardly accessible through a prexyphoid incision. [37]

The long transverse or longitudinal incision scar observed among patients who have undergone surgical treatment of P.E. is unfortunately inevitable when correcting a deformed thoracic cage using conventional methods. This is why the authors of this study recommend the endoscopic procedure whenever is possible, provided there are proper instruments and an experienced working team. [37]

The advantages of this technique include minimal operative scars and the ability to free the pleura from the sternum under endoscopically magnified visualization, which prevents rupturing of the pleura in the retrosternal area. The disadvantages of the technique are increased surgical time, possible pleural perforation and an increased blood loss in elder children. Postoperative results after long-term follow-up (18 months) were good. [37]

The use of the Marlex mesh for the support of the sternum after PE surgery was introduced by Francis Robicsek . A transverse cuneiform osteotomy of the sternum at the beginning of it's abnormal downward curve is performed . Care is taken to do the osteotomy in a line that falls to an intercostal space rather than at a chondrosternal junction.

The xiphoid process is detached from the sternum and is allowed to retract downward. The tip of the sternum is then lifted with a towel clip and with blunt and sharp dissection , the sternum is freed of its mediastinal, perichondrial and intercostal attachment.

The bone is then bent forward to a slightly overcorrected position.

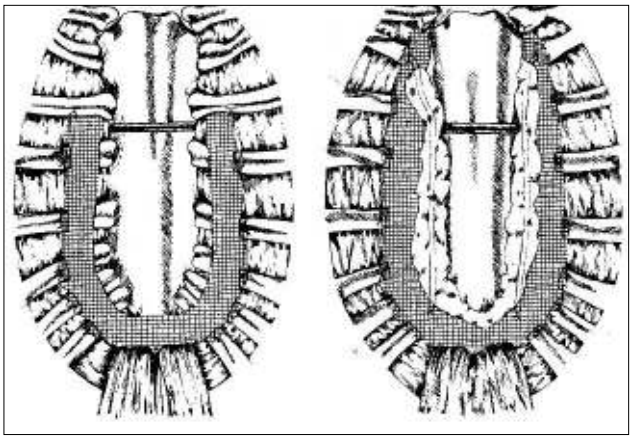


Fig 5 Marlex mesh support [38]

The right pleural cavity is entered deliberately and drained through an intercostal water-sealed catheter to prevent accumulation of blood in the wound itself and to assure undisturbed wound healing. [38]

To stabilize and maintain the sternum in its corrected position , a piece of Marlex mesh is cut to approximate size, placed under it and sutured under slight tension to the distal ends of the divided costal cartilages with nonabsorbable heavy filament. If the pectoralis muscles are well developed, they are joined together in the midline, above the sternum . If they are hypoplastic, they are reattached to the sternal edge. [38]

Long-term follow-up was obtained for 161 patients who underwent a modified Ravitch repair of pectus excavatum. In all cases, the substernal strut was fashioned from a Dacron vascular graft. [39]

A piece of Dacron vascular graft , usually 8 or 10 mm in width, was sutured taut, to the 4^{th} and 5^{th} ribs, to form a substernal strut, using Vicryl or Dexon sutures. The wound was closed in the standard fashion, over subcutaneous drain. [39]

The follow-up period was 12 months to 21.5 years. One hundred thirty-three patients (83%) had satisfactory chest contour; 17 had a fair result, and 11 had frank recurrence. Risk factors for poor contour were an asymmetrical defect, a severe defect, and associated congenital anomalies. [39]

The use of a Dacron strut is relatively easy and complication-free. It can be left permanently in situ. Long-term results have been good, except in patients with an extensive or asymmetrical deformity, and in those with other congenital anomalies, especially Marfan's syndrome. [39]

Isakov et al. introduced in 1980 a new technique for the repair of PE with the aid of permanent magnets.[40] The rib cartilages are mobilised after moving sternal muscles aside Double chondrotomy (near sternum and along the external boarder of the deformation) of deformed rib cartilages is performed when the deformation is flat .If

the deformation is "deep " the rib perichondral resection of rib cartilages is performed . [40]

In all cases cross sternotomy is made by Gigli saw, at the level of the upper boarder of deformation. The magnet plate is put into the retrosternal space so that the upper edge is situated at the level of the sternotomy and it's lower one does not protrude from beneath the sternum more then 0.5-1.0 cm. [40]

The wound is sutured without drainage. The brace with external magnetic system is put on when the patient is on the operating table. The external magnetic system is set up so that the sternum is on he state of moderate hypercorrection and it does not float during breathing .

The extension of sternum is made from one month in younger patients to 1.5 month in older ones. The patient is allowed to sit up 3 days after the surgery and walk after 5 days .The plate is removed between the 6 and 8th month after the operation. The number of patients operated with this technique is 35. The results according to the author were good in 33 patients. [40]

In 1992 M.L. Bentz publishes an article in the British Journal of Plastic Surgery in witch he underlines the fact that the vast majority of patients with PE undergo surgical treatment because of esthetical reasons and analyses the opportunity for plastic surgery approach for the treatment of this condition.

An approach for the treatment of PE with regards to esthetical appearance is proposed by plastic surgeons in cases in witch no respiratory or cardiac symptoms are associated. The first case reported belongs to Murray in 1965 when he describes the use of silicon implants.

Chavoin [42] repots great results on short term as well as on long terms using the silicon implant for the treatment of PE.

The procedure begins with the measurement of the skin thickness in the area of the sunken chest using a special clipper . This is a very important step because of the fact that the thickness of the skin varies as we move towards the lateral side .If this fact is not taken into consideration the implant might not have a correct position on the sternum. [42]

A cast of the sunken region of the chest is made with plaster and shaped manually into the desired shape. The final implant is made of silicon. [42]

For the positioning of the implant a small incision is made at the level of the xiphoid, anterior to the insertion of the abdominal muscles. The muscular mass is the dissected until the costal cartilages are evident and the pectoral muscles are detached up to the second rib. [42] The implant is then inserted into the obtained pocket under the muscles and anchored in place. If the muscles are well developed they can be sutured on top of the implant hence giving it a better anchorage, if they are hypoplasic then they are anchored laterally.

External compression is sometimes required for short amounts of time after surgery using sand bags. [42] The results according to the authors are very good.

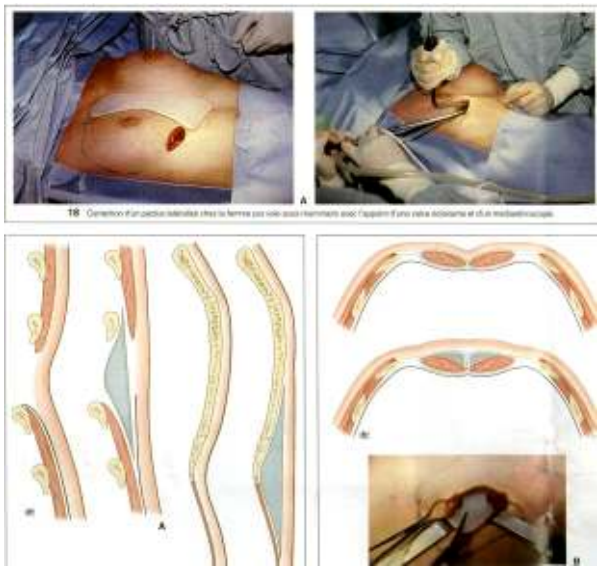


Fig. 6 Silicon implant for the correction of PE [42]

Yamamoto et al. introduced in 1995 the technique for the correction of PE using instead of soft tissue augmentation of the depressed chest a deepithelialized latissimus dorsi myocutaneous flap. The muscle was harvested from the left side because the majority of patients were right handed. [43] The skin at the anterior borders of the latissimus dorsi muscle was incised and the thoracodorsal vessels and nerve were preserved . The whole body of the muscle with overlying adipose tissue was harvested ,and the insertion of the muscle was detached from the humerus . [43]

The skin islands was deepithelized , and the pedicle was transferred to the anterior chest through a subcutaneous tunnel . Then the flap was adequately tacked

with 4-0 nylon to the pectoral and abdominal fascia to repair the sternal depression through bilateral periareolar incisions , a small skin incision at the supraumbilical area, and the skin incisions where the latissimus dorsi muscle flap was harvested. [43]

The most important problem with this technique are the atrophic changes that take placei the transferred muscle.

Reasonable certainty of an excellent results can be ensured only if a generous overcorrection of greater then 50% volume is transferred to the pectoral region. [43]

Hayashi et al . uses a vascularized rib strut for the repair of PE. [48] A vertical midline skin incision is made to obtain maximum exposure. A transverse inframammary incision may be used in young female patients. The procedure of correction of PE is basically a modification of the Ravitch technique. This includes subperichondral removal of all abnormal costal cartilages, supraxiphoid incision and manual mobilization of thesubsternal space, division of the intercostal bundles, oblique transection of the costal cartilage at the lowest normal rib, transverse anterior cuneiform sternal osteotomy and tripod fixation of the sternum.

The authors dissect the intercostal bundles medial to the IMA on one side to preserve the communication between the IMA and the anterior intercostal branches and lateral to the IMA at the other side to maintain the circulation to the sternum. [48]

After correction of the PE deformity the seventh rib, usually on the left side, is harvested as a vascularized rib strut. A 5cm lateral chest incision just above and parallel to the seventh rib is made and the periosteum is exposed for a length of 15 cm .in the upper margin of the rib, the intercostal muscles are dissected and then the space just anterior to the parietal pleura is divided bluntly to the next lower intercostal space. [48]

An intercostal muscle cuff of 15 mm width is attached to the lower margin of the rib to avoid injuring the intercostal vessels. A flap is raised from the chest wall after the rib is cut posteriorly, and then the internal mammary vessels are severed distal to the bifurcation of the corresponding anterior intercostal branch . The rib strut is positioned under the distal portion of the mobilized sternum and is anchored bilaterally to the fifth ribs with wire sutures. Wire fixation of the sternum to the underlying strut is recommended. The incisions are closed in layers with a suction drain tube placed behind the sternum. [48]

Over the past 25 years, Arnold S. Leonard designed a new operation which does not violate the chest and is combined with a bracing technique. This operation can be carried out in children between 45 minutes and an hour and in adults between 1 and 1 hour and 15 minutes and only requires 1 day hospitalization.

The incision is a bilateral transverse curvilinear incision beneath the breasts, which gives a good cosmetic scar. The lower 4-5 cartilages are removed and the perichondrum or the covering of the cartilages is left in place. Then a wedge osteotomy or wedge is taken out of the sternum and depending on whether there is asymmetry the sternum is tailored obliquely according to the defect. A sheathed wire then is placed behind the sternum and then brought out through the muscles and skin and later attached to a modified brace for a period of 12-15 weeks depending on severity. During that period of time, the cartilages reform in the new position and the defect, thus, is completely corrected. The wedge osteotomy is sutured appropriately. The patients are fit with a brace prior to surgery which is a light vest to which the wire is attached at surgery. Patients can return to work within a week after surgery and children may go back to school within that period of time. Blood administration is unnecessary. The complete healing period is 3 months after which individuals can return to their normal activities. Recurrence is very unusual with this operation because of the wedge osteotomy and the holding of the position by the wire and vest.

In 1994 Matsui and M.Kitano [51] propose a new technique for the repair of PE using a poly-L-lactide plate. Poly-L-lactide, a polymer of lactic acid, shows slow degradation in living tissue. Poly-L-lactide plate of high molecular weight maintains more than 90% of its initial mechanical properties for more than 3 months after implantation. Using struts made from poly-L-lactide plate, he performed chest wall reconstruction in 56 patients: for postoperative chronic sternal dehiscence in 23 and sternal elevation for pectus excavatum in 33 cases. [51]

The postoperative external appearances of the anterior chest were improved in comparison with the preoperative state in all cases. The internal features were evaluated by computed tomographic scan. Neither postoperative wound infection nor respiratory complication was observed, and no tendency for regression of the anterior chest occurred in any of the patients.

In 3 of 56 cases (5.4%; one in the sternal dehiscence group and two in the pectus excavatum group), it was necessary to remove part of the strut because of overgrowth of granulation tissue around the implanted material after 4, 12, and 13 postoperative months, respectively.

In the pectus excavatum group, the computed tomographic evaluations showed that poly-L-lactide strut maintained sufficient strength to support the thoracic wall 5 months after implantation. These findings suggest that the bioabsorbable poly-L-lactide strut is a promising material for surgical treatment of chest deformity. [51]

In 1999 Donald Nuss [55] presents to the world probably the most efficient surgical technique for the repair of PE without the resection of the costal cartilage, with minimal blood loss and with record operating time. Prior to surgery, a stainless steel bar (Walter Lorenz Surgical) is bent to conform to the contour of the patient's chest at the level of the deepest part of excavatum. The bar is selected so that its length is sufficient to extend from the mid-axillary line on one side of the patient's chest to the mid-axillary line on the other side. For the operation, the patient is supine with the arms abducted. Incisions are made on the sides of the chest between the anterior and posterior axillary lines. Large subcutaneous pockets are created anteriorly and posteriorly to accommodate the bar. A clamp is inserted through the intercostal space in line with the

deepest point of the concavity and passed across the mediastinum directly behind the sternum. The passage is monitored with a thoracoscope. The point of the clamp is pushed through the corresponding intercostal space on the opposite side of the chest.

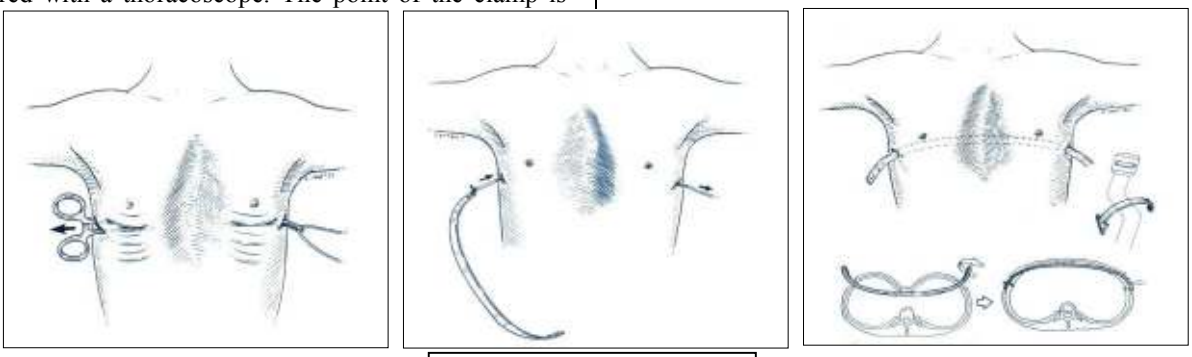


Fig. 9 Nuss procedure [55]

An umbilical tape is then tied to the bar, and the bar is guided across the mediastinum .The convex side of the bar faces posteriorly as it traverses the mediastinum. The bar is then rotated 180 degrees with a vise grip or rotational device so that the convex surface elevates the sternum. Before the incision is closed, a positive end expiratory pressure of 5 cm of water is added to eliminate air from the chest. The surgical wounds are then closed in layers. Analyzing Till's results [56] with the Nuss technique we noticed a minimum blood loss, an average surgery duration of 57 minutes, no complications during surgery , very good esthetic results, no trauma for the patient with a fast recovery and without wide incisions. Thus, it can already be affirmed that this is the actual golden standard for the surgical treatment of pectus excavatum.

Conclusions

Today, high efficiency means an early discovery of the growth disturbances of chondrocostal cartilage and their immediate solving, preferable with minimum invasive procedures. Both the open technique and that minimum invasive– Nuss, require periodic and systematic reevaluations with the purpose of increase in surgical performance, meaning a maximum reduction of application difficulties as well as a decrease in complication during and after surgery.

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