Special techniques in the funnel chest deformity

6

6.1 The Ravitch procedure

Anton H. Schwabegger

With the triumphal march of the surgical method (MIRPE) in the correction of pectus excavatum deformities, according to Donald Nuss [6] the method originally described by Ravitch in 1949 and 1958 [9, 10] was partially dislodged into the background and minor scope was left for special applications only. However the Ravitch technique is still widely used as a standard procedure in the correction of pectus carinatum deformities (Chapter 7.1) Although a recent study consisting of a systematic review and meta-analysis methodology confirmed that the complication rate in the MIRPE technique is higher than in the Ravitch technique, and the period of requirement of postoperative analgesics seems to be lower than in the MIRPE collectives, a clear difference concerning the aesthetic outcome could not be elaborated. It seems that particularly the parameters of pain and aesthetic result, being of paramount importance for the patient self, could not be studied comparatively due to too many biasing factors and lack of long-term comparability [1, 5]. Despite that the MIRPE technique offers a method requiring far shorter surgery time and represents an overall elegant method with however pleasing results lasting for many years. The elegancy and straightforward technique in experienced hands with relatively hidden scars supported its triumphal march so far, convincing patients and surgeons as well. However, these findings are predominantly true for children and adolescents, but must be regarded differentiated in adults. For the latter collective of patients no comparative data are yet available.

The Ravitch procedure is a method to correct either keel or funnel chest deformity by subperichondral resection of the overabundant length of several rib cartilages and thus causes therewith a diminuation of the surface area from a concave funnel or a convex keel into a flat plane. Essential within this method is a horizontal sternum osteotomy in combination with parasternal subperichondral either chondrotomies or chondrectomies at individual levels, depending on the shape of the deformity. While through the implantation of a metal hardware, the so-called pectus bar (Chapters 6.2–6.4) an arching of the funnel deformity into a flat or slightly convex shape is produced and therewith also an advantageous expansion of the thoracic cavity is produced. On the contrary, in the Ravitch method such additional intrathoracic space is accomplished to a minor extent because almost no extension of the thoracic cavity is feasible without such a distension device, which a pectus bar represents. In spite of the nowadays very widely used MIRPE method [6], according to Ravitch, indications still exist for the application of this conventional technique without the use of a metal bar. Certain patients or parents refuse the implantation of metal hardware itself, are alienated by the potential complications of the endoscopically assisted intrathoracic manipulation, or simply show somatic intolerance or known allergic reactions against metal ingredients like the component Nickel.

However, the Ravitch method still suits very well for purely aesthetic corrections of minor funnel deformities (Figs. 1 and 2), in children as in adults, when alternative methods such as custom-made silicone implants (Chapter 6.5) are rejected by the patient or the alternative of lipofilling (Chapter 6.6), based on lacking autologous fat in slim or athletic patients, herein yet in adolescents and adults, is not feasible. A further indication for the utilization of this conventional technique exemplarily is a simultaneous intervention in patients with open heart or vessel surgery simultaneously suffering from a funnel chest deformity (Chapter 6.7). Occasionally and predominantly patients with pectus excavatum prior to all pectus deformities after decades of long course may show unrecognized heart valve problems [2, 3, 8, 12, 13, 16] so that in the midlife adulthood then a heart valve operation becomes necessary. On this occasion also the funnel deformity can be corrected simultaneously with the conventional method [7, 11]. On the other hand, an arching of the funnel deformity with a metal pectus bar placed horizontally at the anterior thoracic wall in these patients operated at the greater vessels or heart represents a contraindication. Because in the eventual case of an acute intrathoracic complication, an immediate surgical intervention

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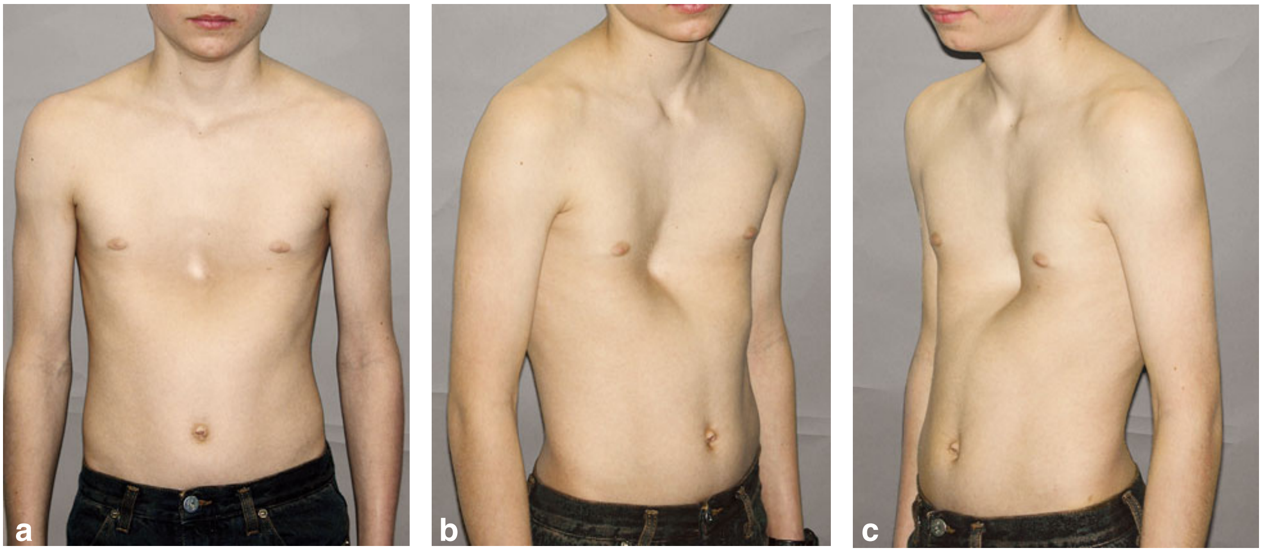

Fig. 1a–c. 14-Year-old male with major pectus excavatum deformity presenting with a steeply plunging funnel causing restriction of cardiopulmonal function. The parents refused invasiveness through MIRPE, thus the conventional Ravitch technique was planned

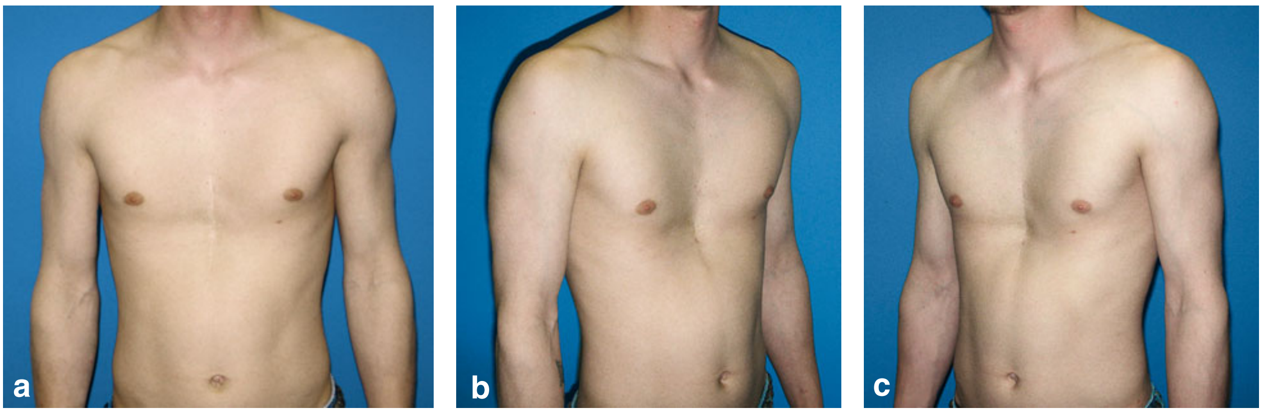

Fig. 2a–c. Same patient 7 years after the Ravitch procedure with stable situation and overall patient satisfaction, but objectively minor relapse. Patient is working as a mason without cardiopulmonal impediments

into or within the thoracic cavity is then blocked by the presence of such metal hardware and may even complicate acutely necessary radiographic or magnetic imaging. Furthermore delivery of cardiopulmonary resuscitation in such patients with a pectus bar in situ seems to be extremely challenging due to its rigidity, however designed to withstand any reflexing forces of the thoracic skeleton [17]. Alternatively absorbable plates and screws (Chapter 6.2) can be used [3, 13, 14] herein, which can be cut or transsected easily in the case of an acute intervention with conventional instruments or do easily give way to resuscitation maneuvers.

6.1.1 Surgical technique of the Ravitch procedure

In male patients, a vertical midsternal skin incision is preferred (Figs. 1–3), but may be modified according to the desires of a patient into an oblique or a horizontal fashion (Chapter 5.1). In female patients, on the other hand the image of the décolleté should remain scar free, thus the surgical access becomes somewhat awkward through modified unilateral or bilateral curved incisions, in order to hide the scars along the submammary crease likewise to the incisions performed in the keel chest deformity (Chapters 5.1, 7.1, 7.2 and 9).

Fig. 3. Extent of number and length of rib cartilage resection in the Ravitch procedure. Also note both the horizontally orientated bony wedge resections at the 3rd and 5th intercostal spaces as well as the resected xiphoid

The dissection of the skin and fat flaps off the musculature succeeds in a usual way. In minor to moderate deformities [15], the subsequently necessary chondrotomies and chondrectomies may be accomplished also by means of the muscle split technique (Chapter 7.2). Each individually disfigured and dissected rib cartilage becomes exposed with a door-like incision at the perichondrium (Fig. 4a). The elevation of the cartilage succeeds with a raspatory (Fig. 4b) while resection is performed using a rongeur. The transsection ideally takes place by means of small scalpel (Fig. 4c) or diathermic cautery. That much of cartilage must be resected and that many incisions at the remaining rib cartilage must be performed that an unbending of the deformed rib portion is enabled without essential tension (Figs. 5 and 6). Prior to any unbending of the deformed anterior thoracic wall, a horizontal osteotomy must be undertaken at the location, where the sternum is inclinated to dorsal. This succeeds with oscillating saws and is carried out solely at the ventral compacta and the Cancellous bone. Such a horizontal osteotomy requires a bony wedge resection (Figs. 5 and 6) in order to allow a forward bending and elevation of the depressed sternum.

At the same time it is to be avoided herewith that also the dorsal compacta will be transsected, because otherwise through dislocation of the mobilized distal sternum part an unsightly and well palpaple ridge may develop, moreover a painful pseudarthrosis might remain. In a

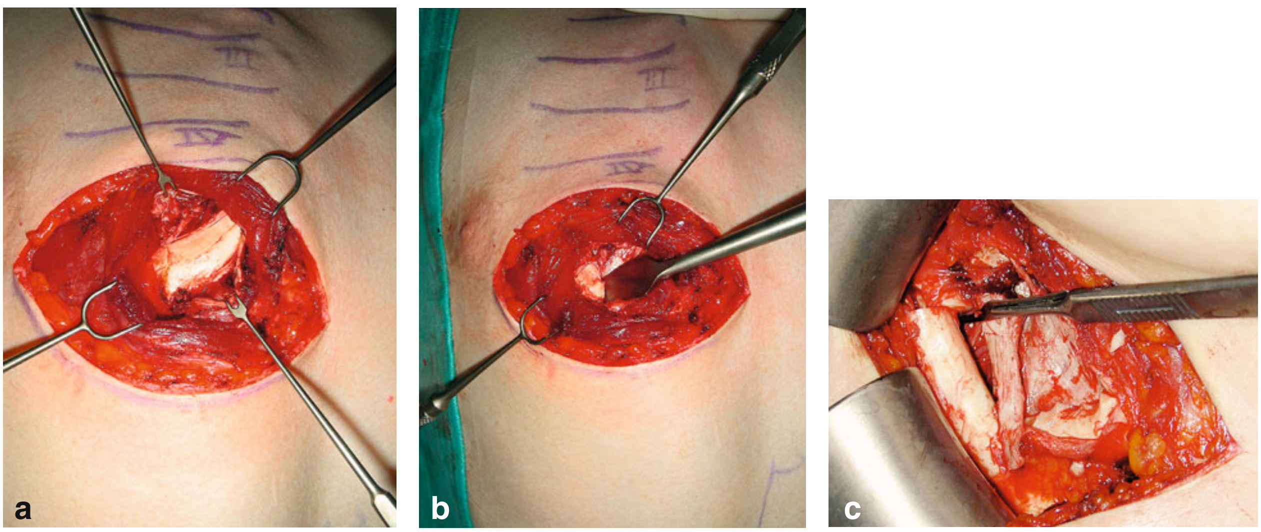

Fig. 4a. Door-like incision and dissection of the perichondrium via the muscle split access to expose the deformed rib cartilages at each individual level. b Dissection of the deformed rib cartilage and elevation out from the perichondrium tube. c Transsection of the rib cartilage by scalpel with particular attention not to damage pleura, internal thoracic vessels, and intercostal nerves

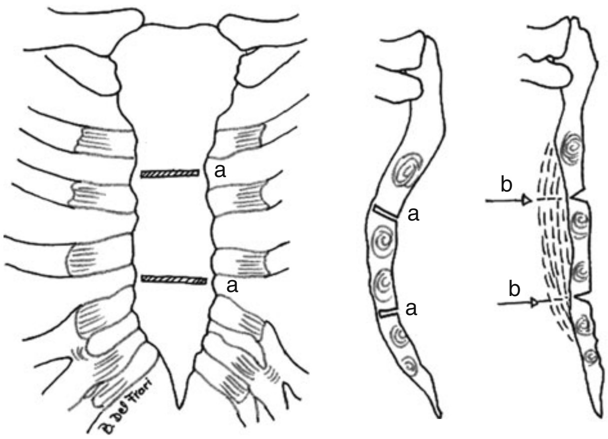

Fig. 5. Schematic depiction of horizontal osteotomies (*a*) at the sternum, the level of singular or multiple incisions may differ depending on the shape of deformity and aimed remodeling. Unbending (*b*) of the incised part of the sternum with green-stick fracture of the dorsal lamina in order to create its final shape

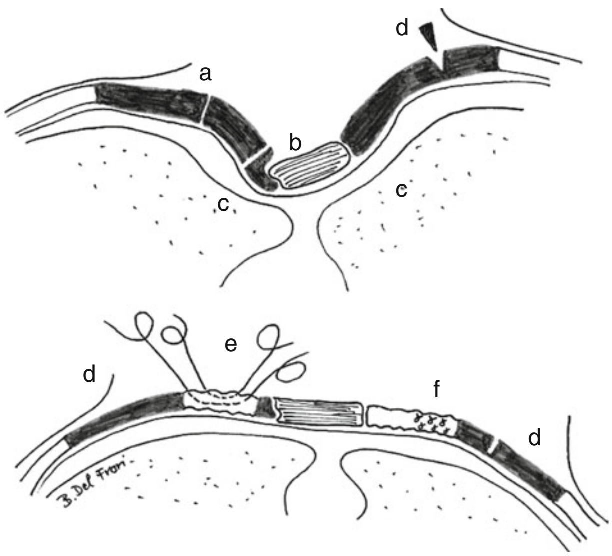

Fig. 6. Deformed cartilages with abundant length (*a*) will be partially resected and for the case of sternum malrotation (*b*) a horizontal osteotomy must be performed. The lungs (*c*) will follow the remodeling procedure. The remaining rib cartilages, if still showing protrusion, need wedge resections at single or multiple sites (*d*) to allow unbending and giving way to the shortening effects on the perichondrium tubes by reefing sutures (*e*, *f*)

female, for the case that the surgical incision was selected to be placed at the submammary crease, the access to a far cranially sternum osteotomy is impeded by an oblonged subcutaneous tunnel. Herewith the utilization of angled oscillating saws is strongly recommended (Fig. 16 in Chapter 7.2) in order to avoid undue skin overexpansion or malplacement of the osteotomy itself. After osteotomy and multiple chondrotomies and/or chondrectomies, the elevation of the now loosened sternum follows by digital mobilization and separation from the mediastinal organs. Subsequently the elevation of the sternum into the horizontal plane is managed for instance with a bone hook and is held in this position now. Simultaneously with unbending the inclination of the sternum, the dorsal, however not transsected compacta, breaks similar to a green-stick fracture but must remain without any dislocation. In contrast to the limited incision at the bone, the dorsal compacta may or in distinct cases even has to be transsected, particularly in cases when malrotation or major twisting of the sternums exists along the longitudinal axis or deviation out of it to lateral is present. Especially in these cases where the dorsal compacta is subject of total transsection, the use of osteosynthetic material, either wires, strong sutures, or plates (Chapter 6.2) is unconditionally necessary for the prevention of relapse of the deformity or unintentional malrotation through muscle tension. In such cases with major deformities and sternum malrotation, a three dimensional CT-scan, utilizing the volume rendering mode in order to accurately depict especially the cartilagineous structures is mandatory [14]. Such an imaging will alleviate the preoperative planning of the extent and site of chondrectomies, chondrotomies, and finally the osteotomies at the sternum (Fig. 7 in Chapter 3.3). The perichondrium tubes are then shortened with heavy absorbable PDS suture, the so-called reefing sutures (Fig. 5).

For the case that by these reefing sutures the elevated sternum cannot be held in the desired position, it can additionally be mounted with the aid of absorbable plates or mesh and screws (Chapter 6.2) in the zone of the sternum osteotomy.

After completion of the remodeling process the muscles are sutured or refixed in anatomically orthotopic position.

The elevation and an even intended slight arching forward of the anterior thoracic wall using the Ravitch procedure especially in adolescents and adults hardly (Fig. 7) succeed to the same extent as such is feasible with the suspension of pectus bars, either applied endoscopically or with an open access. Therefore the patient prior to selecting an appropriate method and prior to planning a surgery has to be informed on the circumstances of limited extent of remodeling capacity using the conventional Ravitch procedure, particularly

Fig. 7. 27-Year-old male, corrected with the conventional Ravitch technique, 1 year after surgical correction of a pectus excavatum deformity, resulting in major improvemet of the deformity. The still present depression may be due to lacking internal suspension in already matured and rigid skeletal structures

in adults. However a distinct improvement of a funnel deformity may yet be achieved but with probably higher incidence of at least partial relapses by time, in contrast to and according to the actual experiences with the methods using metal hardware for sternum suspension.

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6.2 Modifications of the Ravitch procedure and similar methods

Anton H. Schwabegger

There is no ideal method for all seasons.
Ancient medical wisdom

Several modifications of the conventional however genial Ravitch procedure have been developed over the last decade, all of them intending to support the elevated sternum with a diversity of materials. The conventional technique is based on rigid remodeling utilizing reefing sutures to produce a jumping sheet-like flat anterior thoracic wall. The tight reefing sutures aim at long-lasting tension and scarring with a permanent result. Such intervention may be feasible in children with plasticity of immature thoracic skeletal structures, a rapid healing process, and almost neglectable biomechanical strains from the musculature. In contrast to that in adults such reefing sutures, even with the aid of sternal bone relaxation by osteotmies, will hardly result in sufficient sternum elevation and moreover the long-term result is endangered by the rigidity of the adjacent skeletal components, the biomechanical memory of artificially bended cartilage and the muscular strength. In order to support any remodeling in adolescents and adults, metal wires or struts have been advocated since the mid of the last century [1, 3, 4, 7–9, 11, 16, 18, 20, 21, 23, 24] and have found continuation in the finally refined MIRPE technique, ultimately avoiding major surgical invasiveness of a remodeling procedure to the anterior thoracic wall. Bioabsorbable sheets and plates [5, 13, 14] or non-absorbable Marlex® [17] or similar alloplastic material shaped as mesh, threads, or straps may also serve to support the sternum and to prevent re-depression. Even autologous materials like rib struts [6, 15] or fascias to be placed underneath an elevated sternum have been used. However, also such autologous tissue may be well utilized in children with sufficiently pleasing results, but will be suitable not at all for an appropriate correction in adults because of the above-mentioned reasons.

The Hegemann procedure [8], performing a combined approach finally gave way to a nowadays-established technique worldwide, a method ideally suitable for many types of deformities, but gradually and to a major extent replaced by the MIRPE technique already. This

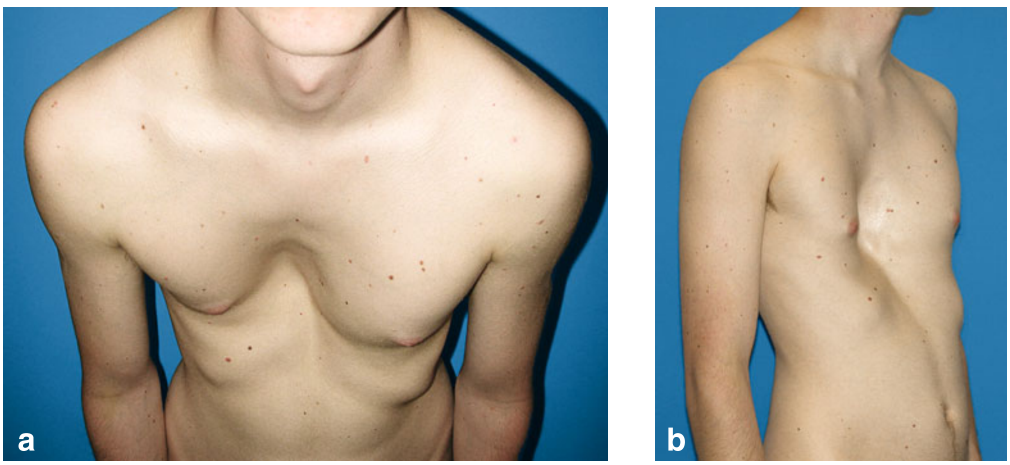

Fig. 1a and b. 20-Year-old male with severe asymmetric pectus excavatum and manifest Nickel allergy, inaccessible for the utilization of metal hardware to correct the deformity

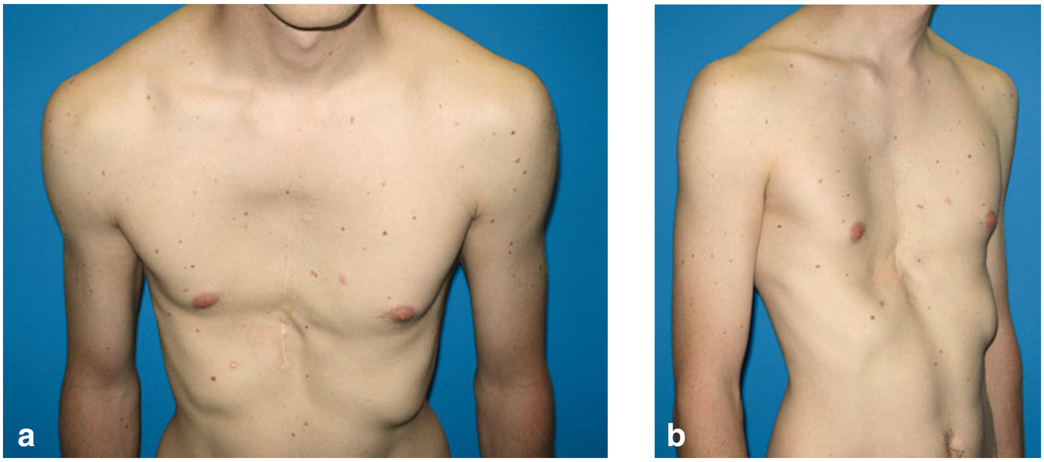

Fig. 2a and b. Same patient with moderate aesthetic result, 1 year after modified Ravitch repair, using a bioabsorbable mesh plate to fix the derotation of the elevated sternum

ingenious combined technique, described and advocated by Hegemann in 1965 [8] and Willital in 1981 [24], relies basically on the Ravitch technique, but complemented with a horizontally placed short metal strut, implanted transsternally with lateral rest on the ribs, which form the funnel margin. Other authors were more invasive in utilizing even two further parasternal metal struts to fix the multiply chondrotomized rib cartilages into a frontal plane [20].

Within all of these variants, the sublay of material of large surfaces, that need sternum and attached ribs to be separated from each other, should be avoided. Such a wide ranging detachment leads to disruption of the terminal branches of the intercostal nerves from the end organ, the parasternal intercostal muscles and periosteum, and overlying skin (anterior cutaneous branch of the intercostal nerve). Lesser the resulting numbness or lowered function of the affected intercostal muscles annoys the patient, but the more will potentially growing neuromas after years lead to cumbersome disturbing pains with abuse of analgetics [19].

A large number of publications so far, impossible to be all cited here, deal with minor modifications of both these basic concepts, namely the loosening of the rigidity of the deformed anterior thoracic wall with multiple incisions of cartilages and bone, and furthermore the support of the sternum in order to prevent relapse. Any minor modification should be considered as far as it is known, but must be adapted to the individual requirements of patients and the remodeling procedure, however following the basic principles when alternative and more modern methods are refused or excluded by other reasons.

6.2.1 Surgical technique

Out of a variety of modifications exemplarily a technique with absorbable osteosynthetic material is presented here (Figs. 1 and 2). The surgical approach generally does not

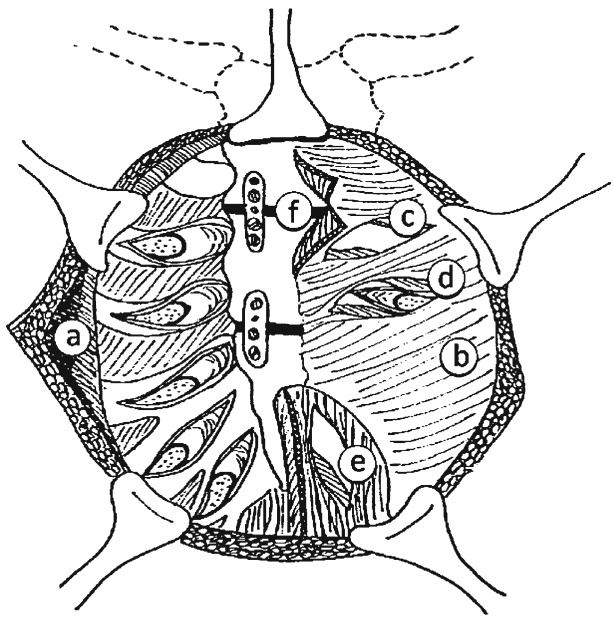

Fig. 3. Schematic overview of conventional technique at the patient's left side and muscle split technique at the right side. (*a*) Retracted pectoralis major muscle and skin flap with rib cartilages resected (*b*). Pectoralis major muscle left in place with several transmuscular splittings (*c*) and (*d*, *e*) muscle split along the rectus abdominis muscle to expose the 7th and 8th rib cartilages, (*f*) slightly elevated periosteum and horizontal sternum osteotomy with absorbable osteosynthetic material

differ from that described already in the previous chapter (Chapter 6.1). Also and preferably the muscle split technique [22] is applied to access the affected ribs, when feasible accordingly to the extent of the deformity. The periosteum is elevated and the sternum is incised at the region of the sternum inclination and if necessary also in a potentially present ascending lower part (Fig. 5 in Chapter 6.1). Prior to the application of the reefing sutures (Fig. 6 in Chapter 6.1), the osteotomized sternum is elevated into a frontal plane either by blunt separation from the intrathoracal organs using the finger, or it may be elevated using a bone hook. Resting in the desired position, the reefing sutures are set. Without relaxation now the osteosynthetic absorbable material is fixed to bridge the osteotomy incisions. For the case, that a bony wedge is resected at the zone of inclination, this wedge may be reimplantated at the lower incision, which is subject of creating a gap due to the unbending maneuver. That piece of bone is then attached and kept in place by the plates (Figs. 3 and 4; Fig. 10 in Chapter 7.2). Particularly in cases with sternum malrotation, when a complete horizontal osteotomy, which includes transsection of the dorsal sternum lamina also is required, the application of an absorbable mesh plate with greater surface is strongly recommended. Especially heat-malleable (PLA/PGA) polymerized glucose-lactide plates (Lactosorb®, W. Lorenz Surgical, FL, USA) can perfectly be adapted to bony incongruences that inevitably result from the derotation maneuver. The greater surface of such a mesh (Fig. 5) contains many more drilling holes than the longitudinal plates and therefore may guarantee much higher stability of the osteotomized and refixed sternum parts for several months and thus until healing of the whole remodeled area [5, 12]. The periosteum is then reattached covering the zone of osteosynthesis and the split muscles are joned with loose adapting sutures. For the case of performed muscle flap elevation to expose a wider area of remodeling, these muscle flaps are united in the midline to cover the whole presternal area, which on the one hand leads to an augmentation of soft tissue volume there in the zone of interest and on the other hand supports rapid healing through the coverage with well-vascularized tissue [18].

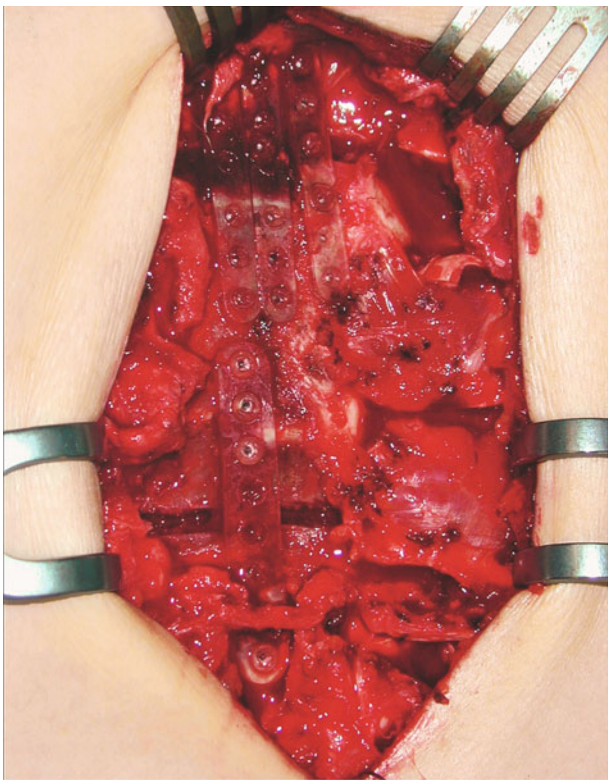

Fig. 4. Intraoperative situs of a modified Ravitch repair of adepressed sternum. Two horizontal wedge resections at the sternum after sternum elevation to a frontal plane are refixed with bioabsorbable plates and screws

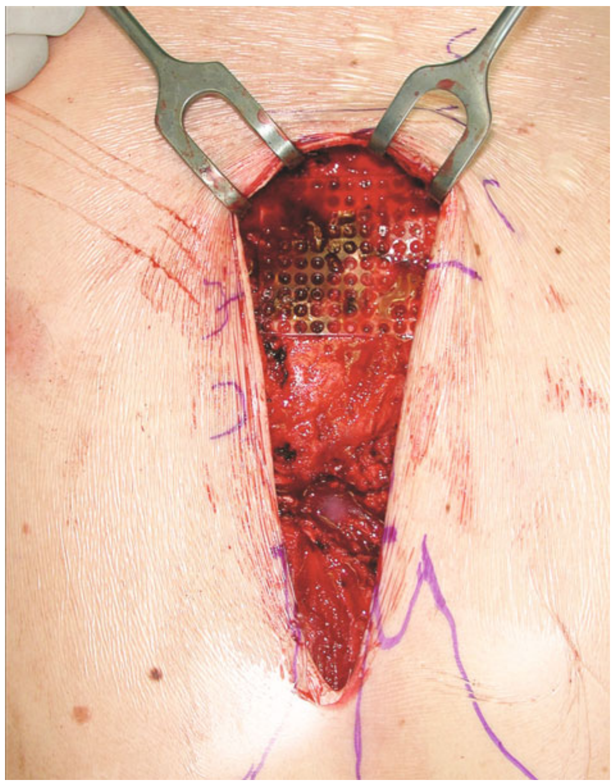

Fig. 5. Intraoperative situs after derotation of a twisted sternum. The fixation is managed with a bioabsorbable mesh, enabling a superior rigid osteosynthesis

6.2.2 Conclusion

A large variety of modifications of the originally described Ravitch procedure exist to correct a funnel chest deformity. Among them the variants that support the position of an elevated sternum with alloplastic material seem advantageous over the conventional method in the generation of permanently pleasing results and in the prevention of relapse, particularly in the collective of patients beyond childhood. No clear evidence but only singular publications [2] in the comparison of different methods are available so far, either due to the diversity of deformities within single institutions or because of different measurement tools worldwide in the evaluation of the outcome of patient satisfaction and objective aesthetic results. The complication rate in utilizing non absorbable materials, in particular with metal struts seems to be higher due to potential migration and dislodgement [13]. This phenomenon is not present with the use of bioabsorbable material, although not providing equal stability than metal devices, they become disintegrated after 1 year and finally will be absorbed completely [10, 12] without producing any known complications so far. However, the choice of an appropriate method should be left to the skilled and well-informed treating specialist, whose decision is based on experience, surgical preferences, available technical equipment, and informed consent with the patient and his/her desires.

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6.3 Thoracic wall deformities

Ann M. Kuhn, Donald Nuss

6.3.1 Introduction

The open technique or Ravitch procedure for the repair of pectus excavatum involved radical resection of cartilages and "short ligaments" and was the procedure of choice until Pena in 1990 and Haller in 1996 [1, 2] drew attention to development of acquired asphyxiating chondrodystophy as a result of this extensive and early resection of the anterior chest wall structures. This was followed by the introduction of the minimally invasive bracing procedure by Nuss et al. in 1997 [3]. The technique has been compared to placing braces on the teeth. It requires no rib, cartilage, or sternal resection and consists of placing a curved steel bar under the sternum using thoracoscopy for guidance [3–5]. The procedure has since gained acceptance by the surgical community [6–10] because of good to excellent long-term results in over 95% of patients.

6.3.1.1 Indications for surgery

During the latter half of the twentieth century it was common practice for surgeons to operate on very young pectus excavatum patients based simply on their clinical evaluation [11, 12]. Since publications by Haller et al. and Martinez et al. drew attention to the risk of acquired asphyxiating chondrodystrophy [1, 2], most surgeons who still use the open technique wait until after puberty to perform the operations. Although the minimally invasive procedure can be performed at any age without risk of chondrodystrophy, the optimum age is just before puberty since the chest is still soft and malleable, the patients show quick recovery, the results are excellent and the risk of recurrence is very low. Patients who have their repair at a younger age and who have their bar removed before puberty are at a slight increased risk of recurrence.

The decision for surgical repair of a pectus excavatum not only relies on the history and physical exam but also strict objective criteria based on the results of the chest CT, pulmonary function tests and cardiac evaluation, including electrocardiogram and cardiac echocardiogram (Fig. 1). Anterior chest wall malformations can range from mild to severe and at our institution less than half the patients are severe enough to warrant surgical correction. Cardiac and/or pulmonary compression causes symptoms of dyspnea on exertion, chest pain with or without exertion and lack of endurance. Pul-

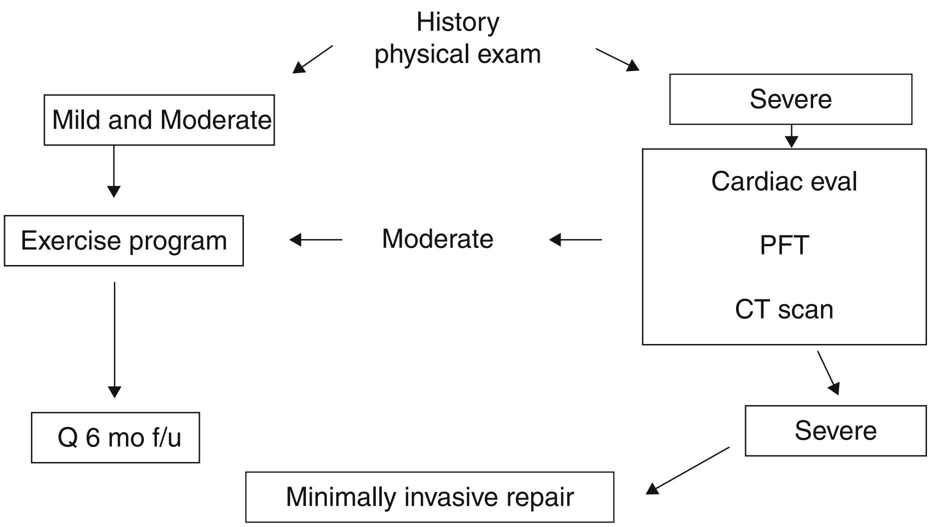

Fig. 1. Pathway for evaluation and treatment of pectus excavatum using the minimally invasive technique

monary function tests often show a restrictive or obstructive deficit. In addition to physical symptoms, a severe deformity may result in poor body image that impacts self-worth [13]. Patients undergoing rapid growth need to be re-evaluated at regular intervals since the deformities tend to progress as the patients grow. This can be especially noticeable during the pubertal growth spurt when a pectus excavatum can progress from mild to severe in as little as 6–12 months.

Classification and treatment algorithm

Initial evaluation of the patient requires a complete history and physical examination including photographs to document the pectus excavatum. Patients are then classified into mild, moderate, and severe categories. The patients with a mild or moderate deformity who are asymptomatic are started on an exercise and posture program and re-evaluated at 12-month intervals. The exercise program is initiated to improve cardio-pulmonary function, chest expansion and to strengthen the chest and back muscles in order to halt the progression of the deformity. Approximately 66% of the patients from our community are treated conservatively. The patients with a severe deformity and patients who have documented progression of their deformity undergo a workup to see whether they have objective evidence to support the need for surgical repair. The workup includes pulmonary function studies, a cardiology evaluation by a cardiologist, including an electrocardiogram and echocardiogram, and finally, a chest CT scan. For consistency, radiologists have suggested that the chest CT be performed during quiet respiration, not during maximum inspiration (Fig. 2). The need for surgical correction is determined if the patient has two or more of the following criteria: (1) a Haller index of greater than 3.25 demonstrated by CT scan; (2) cardiology evaluation demonstrating cardiac compression or displacement (Fig. 3) mitral valve prolapse, murmurs or conduction abnormalities; (3) pulmonary function studies showing restrictive and/or obstructive lung disease; (4) progression of the deformity with associated physical symptoms other than isolated concerns of body image; (5) recurrent pectus excavatum after a failed previous repair by a Ravitch procedure or a minimally invasive procedure.

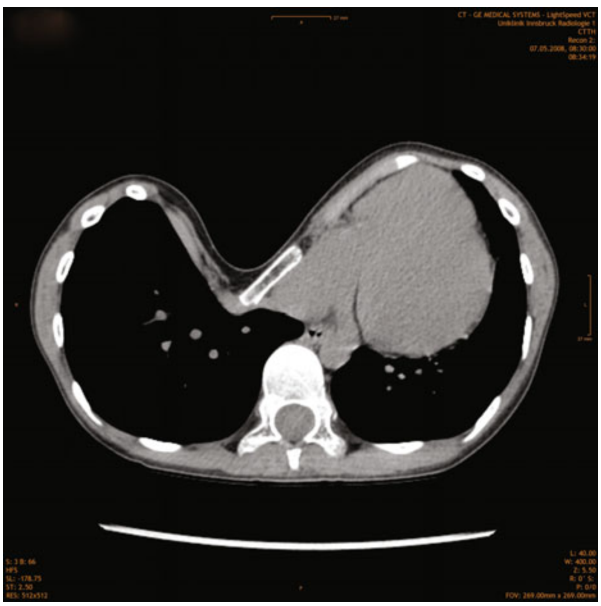

Fig. 2. CT scan showing severe pectus excavatum performed during quiet respiration

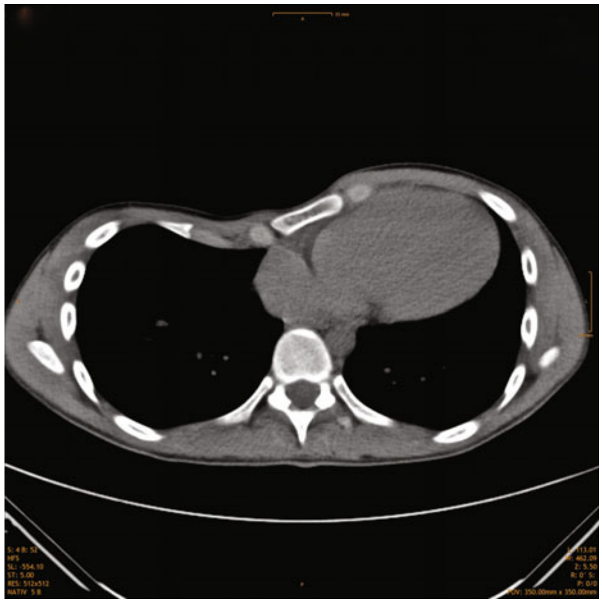

Fig. 3. CT scan demonstrating cardiac compression and displacement, as well as pulmonary compression

Preoperative assessment should also include asking about a history of metal allergy in the patient and immediate family. Nickel and Cobalt are components of the surgical steel used in the bar and are the cause of allergy in 2% of patients [14]. If a metal allergy is suspected, testing by a T.R.U.E. patch (Allerderm, Phoenix, AZ) can clarify this issue. In the presence of metal allergy, a non-allergic Titanium bar is used instead. Unlike the stainless steel bar, which is bent by the surgeon at the time of operation, titanium, must be bent in advance at the factory using CAD/CAM technology.

6.3.1.2 Exercise program

Most patients with pectus excavatum lead a very sedentary lifestyle and have a classic "pectus posture" which aggravates the deformity and may lead to progression of the deformity. Patients who are diagnosed as having a mild or moderate deformity are started on an exercise and posture program designed to improve cardio-pulmonary function and improve posture. Exercise can also increase chest expansion. Breathing and posture exercises are taught to the patients and they are instructed to do these on a daily basis. Patients are also encouraged to participate in aerobic activities such as team sports that involve swimming, running, etc.

Patients are re-evaluated at 6- to 12-month intervals to monitor compliance with the exercise program and to check progression of the deformity. It is possible to halt the progression in a mild deformity and slow the progression in a moderate deformity.

6.3.2 Surgical repair

Although the minimally invasive procedure can be performed at any age, the optimum age is just before puberty. The chest is still soft and malleable before puberty and the patients show quick recovery, a rapid return to normal activity, and have excellent results. The surgical correction of the pectus excavatum is accomplished by inserting a convex steel bar under the sternum with the convexity facing posteriorly. When the bar is in position, it is turned over 180° thereby correcting the deformity. The technique is made possible by the malleability and flexibility of the anterior chest wall and requires no cartilage incision or resection and no sternal osteotomy. After puberty the flexibility of the chest wall decreases making the repair more difficult and patients frequently require the placement of two bars. At our institution we have performed the procedure up to age 31 with equally good results [4]. Other authors have obtained excellent results in adult patients up to 50 years of age [15, 16].

6.3.3 Surgical technique

The preoperative checklist on the day before surgery includes reviewing all studies, checking for allergies including allergy to nickel, and measuring the chest to determine bar length. A measurement from the right to left mid-axillary line is taken and then 2 cm (±1 in.) is

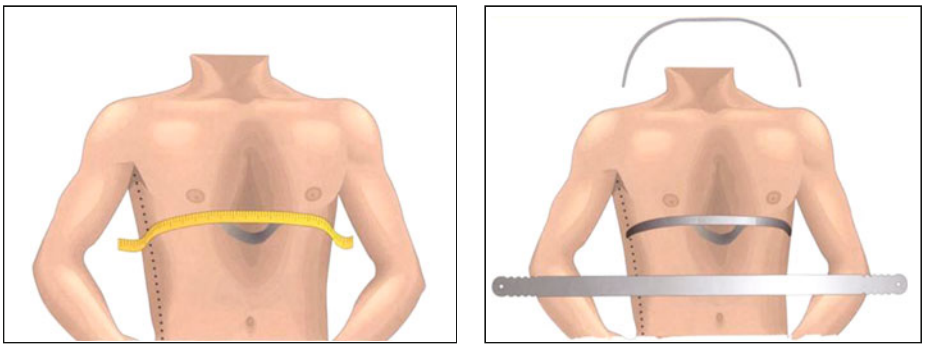

Fig. 4. Technique of measurement determining bar length. The bar needs to be 2 cm shorter than the measurement

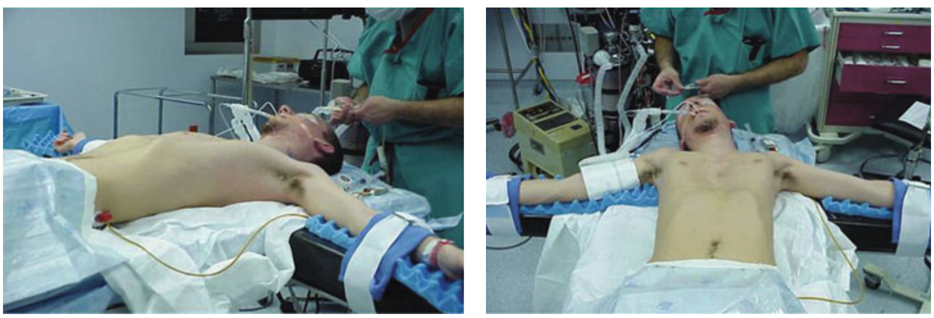

Fig. 5. Positioning of the patient to minimize brachial plexus injury

subtracted from this measurement. The bar takes a shorter course than the tape measure and consequently needs to be 2 cm (±1 in.) shorter than the measurement (Fig. 4).

General endotracheal anesthesia and epidural catheter insertion is undertaken by the anesthesiologist. The epidural catheter infusion is continued for 3–5 days with the average at our institution being 3 days. An indwelling bladder catheter is placed and this remains until postoperative day 1 at which time it is removed. Antibiotic coverage is provided and continued to discharge to minimize the risk of pneumonia with subsequent bar infection. Both arms are abducted at the shoulder and gel pads are used to prevent brachial plexus injury (Fig. 5). There should be slight flexion at the elbows. The patient is draped and the Lorenz™ pectus support bar is bent into a semi-circle, leaving the central 2 cm flat to support the sternum (Fig. 6). Bending the bar into an arch shape allows sustained load bearing of the bar. If the central flat section of the bar is too long, there will be undercorrection of the pectus excavatum.

Fig. 6. Demonstration of a properly bent pectus support bar. The middle bar is correctly bent. The upper bar is too flat, while the lower bar is too rounded

Marking the patient requires determining the deepest point of the pectus excavatum and marking this area with a surgical marking pen (Fig. 7). If the deepest point of the pectus is inferior to the sternum, then the inferior end of the sternum is marked instead. This point sets the horizontal plane for bar insertion. The intercostal spaces that are in the same horizontal plane as the deepest point of the pectus excavatum are marked with an "×". These thoracic entry and exit points on each side of the sternum should be medial to the top of the pectus (costochondral) ridge. Lines are drawn for the proposed incision sites on each lateral chest wall in the same horizontal plane (Fig. 7).

A thoracoscope is inserted through the right lower lateral chest wall approximately two interspaces inferior to the proposed right lateral thoracic wall skin incision (Fig. 8). A thorough inspection of the right hemithorax and mediastinum is performed checking that there is no contraindication for repair. Then pressure is applied to the intercostal spaces marked for bar insertion to ensure that the external markings line up well with the internal anatomy. After confirming by thoracoscopy that the internal and external anatomy match up well, bilateral thoracic skin incisions are made in the region of the mid-axillary line and a skin tunnel is raised anteriorly toward the intercostal space marked with an "×", medial to the top of the pectus ridge (Fig. 9). Also, a pocket is created for the distal end of the pectus bar and stabilizer. Under thoracoscopic

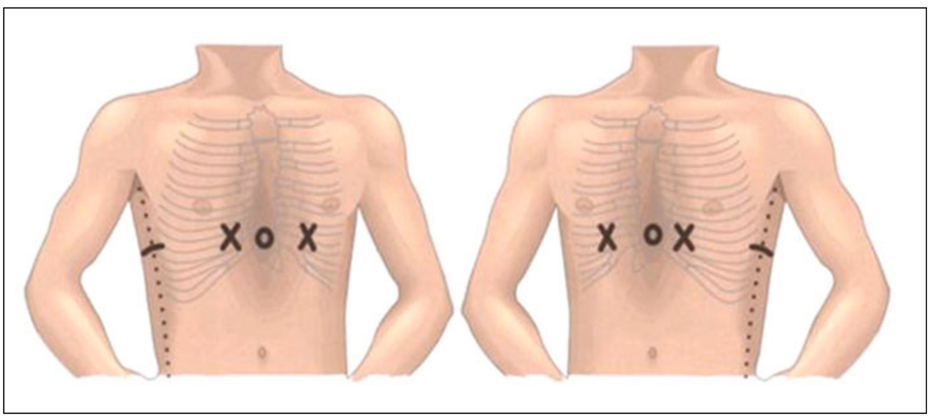

Fig. 7. Marking the bar insertion site. The skin incision, entry and exit sites and the deepest point of excavatum are all in the same horizontal plane

Fig. 8. Placement of thoracoscope for minimally invasive repair

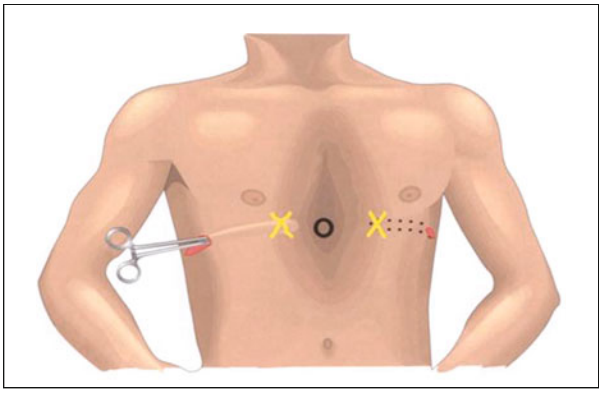

Fig. 9. Creation of the skin tunnel

control, the appropriate size Lorenz™ introducer (Biomet Microfixation, Jacksonville, FL) is inserted through the right intercostal space at the top of the pectus ridge at the previously marked "×" (Fig. 10). The EKG volume is turned up so that the heartbeat is clearly audible. The pericardium is gently dissected off the under surface of the sternum (Fig. 11). The introducer is *slowly* advanced across the mediastinum under thor-

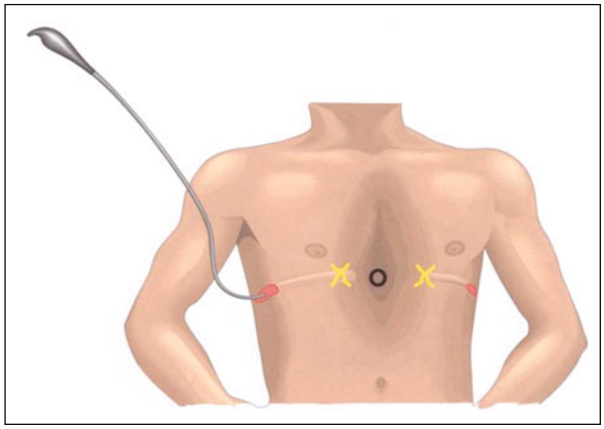

Fig. 10. Insertion of the introducer

acoscopic guidance with the point always facing anteriorly and in contact with the sternum. When the substernal tunnel has been completed, the tip of the introducer is pushed through the contralateral intercostal space at the previously marked "×", and advanced out of the skin incision (Fig. 12).

The introducer is then used to elevate the sternum. The surgeon lifts the introducer on the right side and the assistant lifts on the left side (Fig. 12). The lifting is repeated until the sternum has been elevated out of its depressed position and the pectus excavatum has been corrected. An umbilical tape is attached to the introducer, which is slowly extracted, pulling the umbilical tape through the substernal tunnel (Fig. 13). The previously prepared pectus bar is tied to the umbilical tape and guided through the substernal tunnel using the umbilical tape for traction and the thoracoscope for vision. The bar is inserted with the convexity facing posteriorly. When the bar is in position it is rotated 180° using the bar flipper (Fig. 14).

If the bar requires further bending, it is turned over and molded where required using the small Lorenz bar bender. If one bar is not enough, then a second bar is inserted

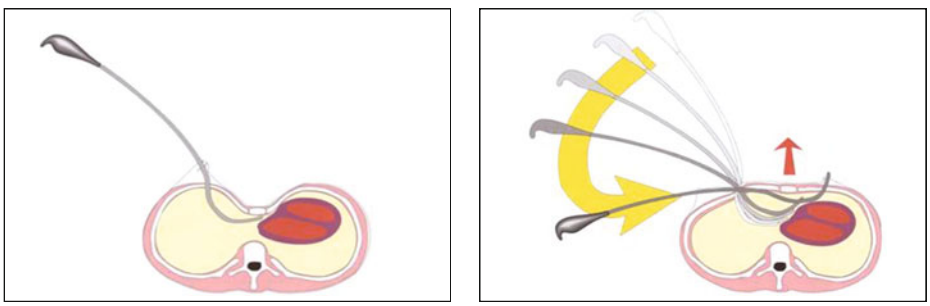

Fig. 11. Technique of dissection with the introducer

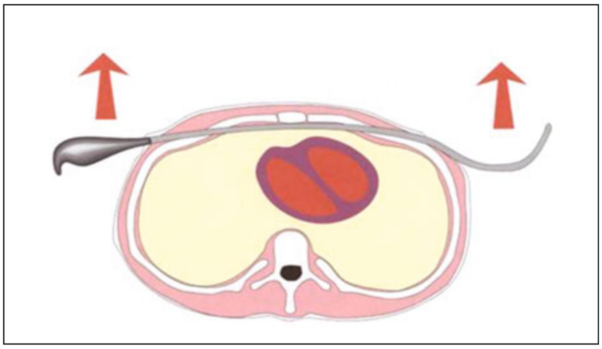

Fig. 12. Demonstration of placement of introducer and subsequent lifting on the sternum

one interspace above or below the first one. Two bars give better and more stable correction, especially in older patients. Slight overcorrection is necessary to prevent recurrence after the bar is removed. Some surgeons prefer approaching the mediastinal tunneling from the left rather than the right side. Other surgeons make a third incision over the xiphoid and then apply a towel clip to elevate the sternum and others do a finger dissection under the sternum before inserting the introducer [17].

6.3.3.1 Stabilization of the bar is absolutely essential for success

A stabilizer is inserted onto the left end of the bar and wired to the bar with No. 3 surgical steel wire. If the bar does not seem stable, a second bar rather than a second stabilizer is probably required. Heavy absorbable pericostal sutures of "0" or "1" PDS are placed around the bar and underlying rib using an "endo-close" laparoscopic needle under thoracoscopic vision on the right side (Fig. 15). Hebra and Gauderer advocated placing a suture adjacent to the sternum [18]. Once the bar is stabilized, the incisions are closed in layers and the pneumothorax is evacuated using the trocar and attached tubing (or a chest tube), with a "water-seal" system. A chest X-ray is obtained before the patient is taken out of the operating room, to check for a residual pneumothorax.

6.3.4 Postoperative management

In the recovery room the patient is kept well sedated with the goal of a smooth emergence from anesthesia.

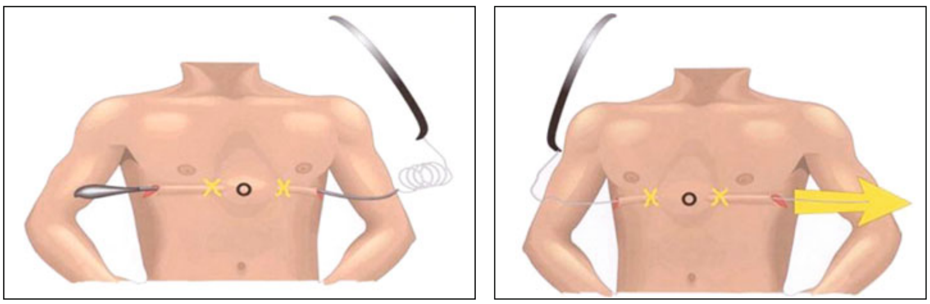

Fig. 13. Technique of using umbilical tape to guide the pectus support bar through the substernal tunnel

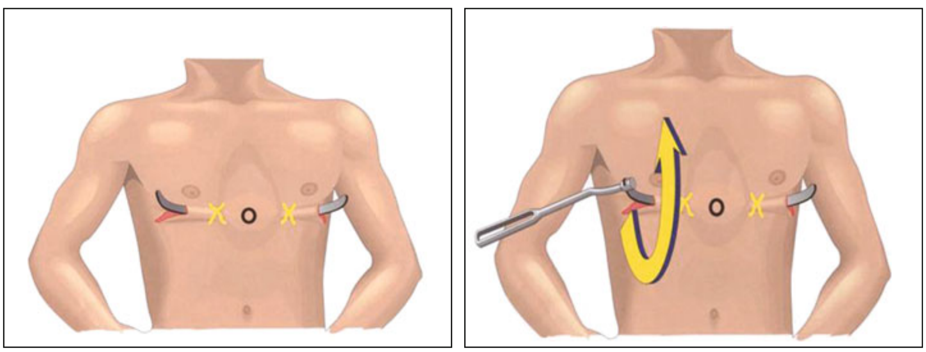

Fig. 14. Rotation of the pectus support bar using the bar flipper. Rotation may be clockwise or counter clockwise

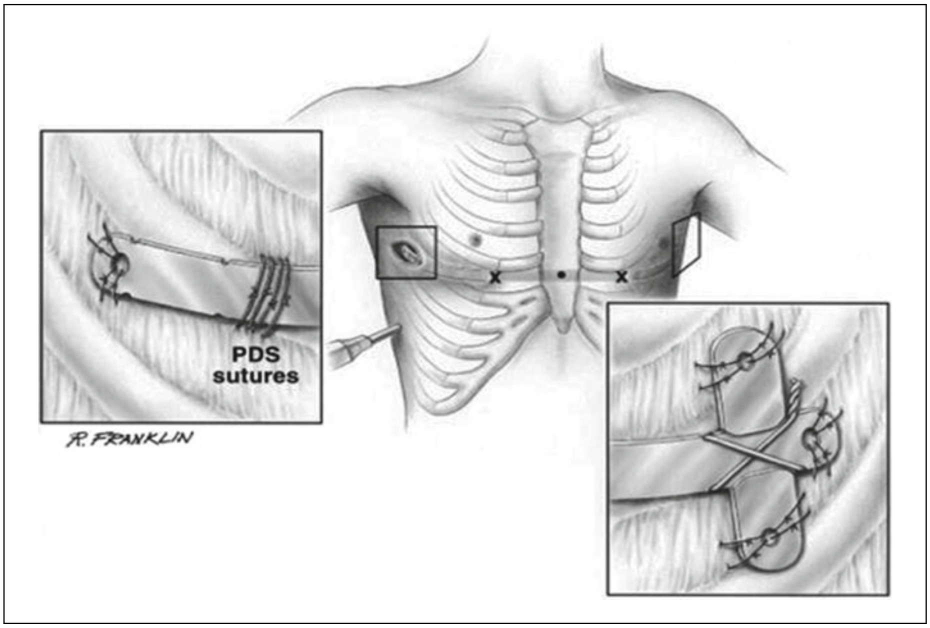

Fig. 15. Stabilization of the pectus support bar

The epidural catheter is left in for 3–4 days. The patient is discharged home on the fourth or fifth postoperative day. Patients may return to school after 2 weeks, but may not participate in sports for 6 weeks from the time of surgery. After the 6 weeks the patients are encouraged to resume their pectus breathing and posture exercises and to participate in aerobic sporting activities (soccer, basketball, and swimming). Heavy contact sports (boxing, American football, and ice-hockey) are prohibited until bar removal.

6.3.5 Technique of bar removal (2–4 years after insertion)

The patient undergoes general endotracheal anesthesia with 5–6 cm of PEEP. The patient is positioned supine with both arms abducted at the shoulder. The chest X-rays are reviewed to confirm the position of the stabilizers. Palpation is then performed to see if bar and stabilizer(s) are palpable and close to the old scar. If the bars and stabilizer are not palpable, then "C-arm" fluoroscopy can be used to determine exact site of the hardware. Use the old scars for incision site if at all possible when removing the bar and stabilizer. The bar ends and stabilizers are mobilized and the wire is cut in two places and removed.

When bar and stabilizer have been freed up from the surrounding scar tissue, the inferior wing of the stabilizer is delivered out of the incision followed by the end of the bar and finally the superior wing of the stabilizer. The stabilizer is removed from the bar. The bar is unbent with the bar flippers or multibenders. An orthopedic bone hook is then passed through the hole in the end of the bar and gentle traction is used to slowly extract the bar. The patient is kept on PEEP until the incision is closed.

6.3.5.1 Timing of bar removal

We advise that the pectus bar be left in place for 2–4 years with most patients having their bar(s) out at 3 years. Patients are evaluated on an annual basis and their growth and activity level are monitored. They are encouraged to do their pectus exercises and to participate in aerobic sports. Patients between the ages of 6 and 10 years and 18 years and older often do not grow rapidly, and they tolerate the bar well for up to 4 years. On the other hand, teenagers who undergo a massive growth spurt (15 cm) may require bar removal after 2 years.

6.3.6 Results

6.3.6.1 Demographics

As of December 31, 2007 we have evaluated 1,941 patients with chest wall deformity. The 1,101 patients have undergone pectus repair, 1,015 have undergone primary operations and 86 have undergone redo opera-

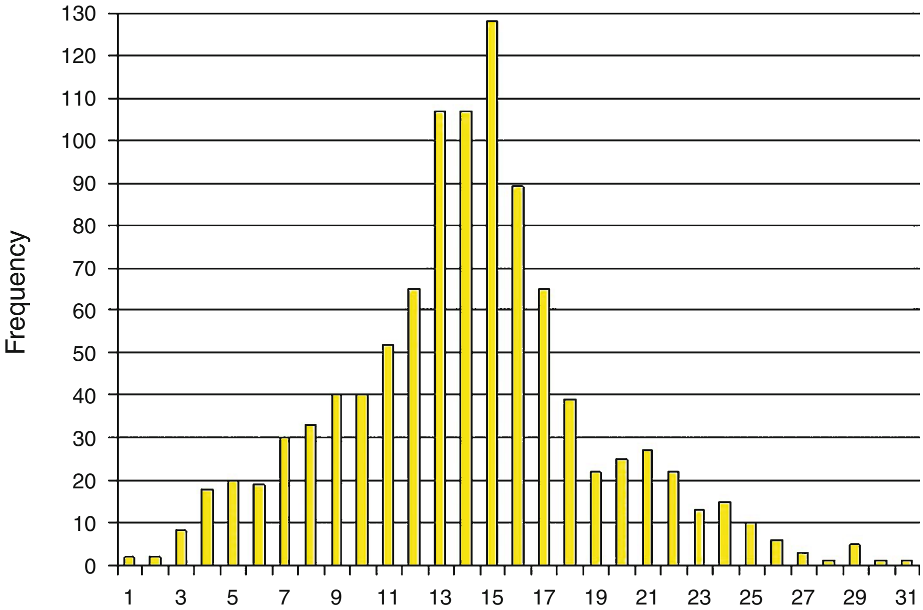

Fig. 16. Graph showing age at primary surgery with a median age of 14 years. Age ranged from 1 to 31 years at our institution

tions. Of the 86 patients undergoing redo procedures, 39 had a failed Ravitch, 44 had a failed Nuss, 1 had both a failed Ravitch and Nuss procedure and 2 had failed Leonard procedure. Of the 1,015 patients having primary repair, 690 patients have had their bar removed. There have been numerous important modifications which have been made both to the surgical technique (e.g., routine use of thoracoscopy) and to the instruments since the origination of this procedure. This has served to facilitate insertion and stabilization of the substernal support bar. These have markedly reduced the risks and complications and have been well documented in recent publications [19].

The male to female ratio in patients undergoing repair was 4:1. The median age was 14 years, with a range of 1–31 years (Fig. 16). The median Haller CT index was 4.6 with a range of 2.4–32.4. Cardiac compression was noted on echocardiography and/or CT scan in 793/889 (89%) patients. Mitral valve prolapse was noted in 132 (15%) patients. Resting pulmonary function testing (PFT) was completed in 900 patients and demonstrated abnormalities in up to 45% of the patients.

6.3.7 Operative procedure, analgesia, and length of stay

A single bar was inserted in 730 (71.9%) patients. Two bars were inserted in 281 (27.7%) patients. Four (0.4%) patients received three bars. Blood loss in most patients was minimal (±10 cc). The median length of stay (LOS) was 5 days with a range of 3–14 days.

6.3.8 Complications

6.3.8.1 Early complications (Fig. 17)

There were no deaths ($n=0$) nor were there any cardiac perforations ($n=0$) during the 1,101 primary and secondary repairs performed at our institution. It was common to have pneumothorax after repair but usually it resolved spontaneously. Pneumothorax requiring chest tube drainage occurred in 36 (3.6%) of the primary repairs and required only percutaneous aspiration in 3 (0.3%) primary repairs. In the redo population, 29 (34%) patients required a chest tube placement for evacuation of the pneumothorax with 2 (3%) resolving with aspiration only. Hemothorax requiring drainage but no transfusion occurred after four (0.4%) primary repairs. Three (0.3%) pleural effusions required treatment by either chest tube or aspiration.

In the population of primary repair patients, pericarditis requiring treatment with indomethacin or prednisone occurred following five (0.5%) repairs, with one requiring pericardiocentesis. Pneumonia occurred after 6 (0.6%) repairs, and medication reactions have occurred following 36 (3.6%) repairs. One

• Pneumothorax w/spont. resolution	60.4% ($n = 613$)
• Pneumothorax w/chest tube	3.6% ($n = 36$)
• Horner's syndrome	17.7% ($n = 179$)
• Drug reaction	3.6% ($n = 36$)
• Suture site infection	1.0% ($n = 10$)
• Pneumonia	0.6% ($n = 6$)
• Pericarditis	0.5% ($n = 5$)
• Hemothorax	0.4% ($n = 4$)
• Pleural effusion (requiring drainage)	0.3% ($n = 3$)
• Temporary paralysis	0.1% ($n = 1$)
• Death	0%
• Cardiac perforation	0%

Fig. 17. Early postoperative complications of primary surgical patients

hundred and seventy-nine (17.7%) patients had transient Horner's Syndrome at varying times during the thoracic epidural administration.

6.3.8.2 Late complications (Fig. 18)

Fifty-eight (5.7%) patients have experienced bar displacement, and 43 (4.2%) displacements warranted repositioning. After the introduction of stabilizers, the incidence of bar displacement dropped from 8.9% to 2.3%. There has been only one bar displacement (0.1%) since we combined placing a stabilizer on the left and PDS sutures around the bar and underlying rib on the right. Bar infection occurred in 11 patients (1.1%) requiring early bar removal in 2 (0.2%) patients. Twenty-nine (2.9%) patients had allergies to the bars. These presented in a variety of ways. Several patients gave a history of metal allergy and therefore received a titanium bar, stabilizer and wire suture. The others were diagnosed postoperatively and were treated with antibiotics or steroids. Three of these patients did not respond to medical treatment and required early bar

• Bar displacements	58/1015 (5.7%)
• Requiring revision	43/1015 (4.2%)
• Overcorrection	32/1015 (3.2%)
• Bar allergy	29/1015 (2.9%)
• Wound infection	11/1015 (1.1%)
• Recurrence	8/1015 (0.8%)
• Hemothorax (post-traumatic)	2/1015 (0.2%)
• Skin erosion	1/1015 (0.1%)
• Accidental death	1/1015 (0.1%)
(accidental death 3.5 years post op)	

Fig. 18. Late postoperative complications of primary surgical patients

removal, two of these received titanium bars. The symptoms resolved after removal of the steel bar. Thirty-two (2.9%) developed a moderate overcorrection of their deformity and four (0.4%) developed a true carinatum deformity.

6.3.8.3 Long-term follow-up

Patients are followed at 6 months postoperatively, and then yearly. Long-term assessments classify the post-operative results as excellent, good, fair, or failed.

A result is considered to be excellent if the patient experiences total repair of the pectus excavatum as well as resolution of any associated symptoms. A good result is distinguished by a markedly improved but not totally normal chest wall appearance and resolution of any associated symptoms. A fair result indicates a mild residual pectus excavatum without complete resolution of associated symptoms. And a failed repair indicates a recurrence of the pectus excavatum and associated symptoms and/or the need for another repair after bar removal.

The initial cosmetic and functional results at the time of repair were excellent in 938 (92.4%), patients, good in 74 (7.3%) patients, fair in 1 (0.1%), and failed in 2 (0.2%). Of these patients, 690 (68%) have had their bars out for more than 1 year. The results of the patients who had their bars removed one or more years ago are excellent in 587 (85.4%); good in 75 (10.9%); fair in 9 (1.3%), poor in 7 (1.0%) and failed in 9 (1.3%). There were three patients who did not return (Fig. 19). Patients who did not comply with the exercise program and had their bar removed before puberty had a higher recurrence rate. The length of time the bar was left in situ had a direct effect on the long-term outcome. The longer the bar stayed in, the better the results. The age of the patient also affected the long-term outcome with the best results occurring in the 7–12 and 13–18 year age groups. The long-term results of patients who have had their bar removed before December 31, 2006 show that

• Total number of primary patients	1015
• Total number w/bar removed	690 (64.2%)
– Excellent result	587 (85.4%)
– Good result	75 (10.9%)
– Fair result	9 (1.3%)
– Poor result	7 (1.0%)
– Failed	9 (1.3%)
– No return (bar removed else w)	3 (0.4%)

Fig. 19. Overall results after removal of pectus bar

Number w/bar removed prior to 12/31/06	587
– Excellent result	493 (84.0%)
– Good result	69 (11.8%)
– Fair result	9 (1.5%)
– Poor result	7 (1.2%)
– Failed	9 (1.5%)
– No return	2

Fig. 20. Long-term results in patients having their bar removed before December 31, 2006

we have 587 total patients with and excellent result in 493(84%) patients (Fig. 20).

6.3.9 Conclusion

The minimally invasive procedure provides good to excellent correction of pectus excavatum in over 90% of patients with no rib resection, no sternal osteotomy, minimal blood loss, and rapid return to normal activity. Studies have shown marked improvement in the patient's body image and have also shown slight improvement in pulmonary function [20]. The 1,101 patients managed at our institution have had excellent long-term results and low morbidity.

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6.4 Special considerations in adults with MIRPE and MOVARPE techniques

Anton H. Schwabegger

The deformity continues to worsen until skeletal growth has been completed in late adolescence and then changes little througout adult life.

Eric W. Fonkalsrud

According to but without knowledge of that fundamental citation of Fonkalsrud [10], many patients and their parents are not adequately informed about the opportunity to correct skeletal deformities of the anterior thoracic wall during growth and body maturation at an age, when surgical repair does not yet mean a major invasive and technically demanding intervention due to skeletal elasticity. Fonkalsrud in 2000 stated that only 15% of all patients affected by the deformity undergo surgery. With the advent of the MIRPE, this percentage initially increased, but on the other hand, also a significant number of present adult patients out of the remnant 85% thus untreated patients now seek for feasible modern treatment.

In almost no case a deep funnel diminishes with increasing age or growth spurt, yet the opposite is the case, as costal cartilages elongate with body maturation thus lead to increasing folding up (keel chest) or down (funnel chest) of the adjacent sternum [12, 37]. While the main advantage of the MIRPE in children is reshaping the anterior thoracic wall without osteochondrotomies and hence allowing for normal growth of the thorax, this advantage of pliability no longer is present in the adult thorax. Herein the size of the thoracic cage is already determined by the rigidity of the skeletal structures and musculature, thus the matured skeletal structures will not simply tolerate any remodeling forces just by transmission of pressure.

The flexibility of the thorax and in particular of the chondrosternal zone at the anterior thoracic wall in children represents the fundamentals for the success of the MIRPE method (Fig. 1a–f). On the basis of this flexibility, the method was developed for the correction of the juvenile pectus excavatum deformity by the pediatric surgeon Donald Nuss (Chapter 6.3). Remarkably he published the first series in 1998 [26], not prior to a very long observation period of up to 10 years, presenting successful and secured long-term results. The incontestable successes of this method now also made many adults, who were concerned by their unpleasant aesthetic burden, attentive to pull this minimally invasive method into consideration as a new option. They apparently preferred this concept with minor scars in contrast to open surgery techniques [6–8, 24, 33, 40] or alternatives such as autologous microvascular tissue remodeling [14, 16, 21, 25, 32, 38], well known so far. Osteochondrotomies in adults will not lead to growth disturbances any more, but may result in other problems like formation of scars in a non concealable area of the body surface, particularly in women and furthermore reduced flexibility of the thoracic wall.

Because of the success with children and youth, multiply published through many scientific papers [12, 26, 31] but moreover in public media, the desires and even demand [19] for the application have markedly increased also in the adult males and females equally [2, 3, 11, 20, 30, 35, 42].

Utilizing the pure MIRPE in adulthood however arise other and substantially more particular problems contrarily to an early age. The standardized fabrication of the pectus bar in uniform material strength and width on the one hand allows the use of instruments of different manufacturers. It furthermore turned out that this uniformity of instruments is advantageous especially for the explantation procedure of the pectus bar after years. Adult patients nowadays hardly any more remain stationary and due to increasing requirements of migration across nations they undergo treatment wherever it appears suitable. Therefore, more frequently pectus excavatum patients present themselves, primarily treated elsewhere or even abroad and claim to have the bars removed at the end of the implantation period after several years. Fortunately through the uniformity of the pectus bars and the instruments though fabricated by several manufacturers, this migration of patients until now yields no problem. For exactly these circumstances

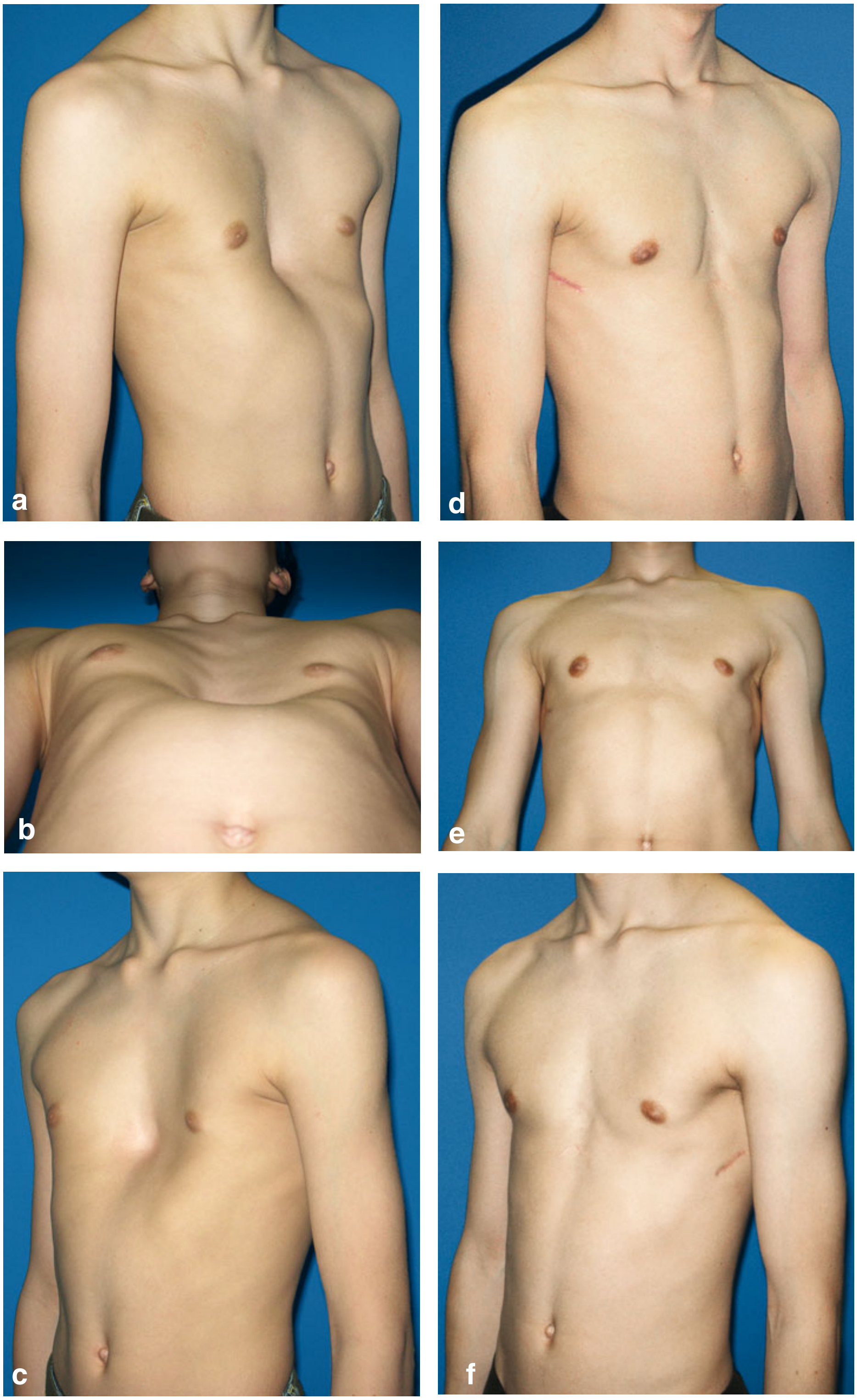


Fig. 1 (a–f). 13-Year-old male with moderately asymmetric funnel chest deformity (**a–c**). Situation at an age of 17 years and 1 year after explantation of the pectus bar (**d–f**)

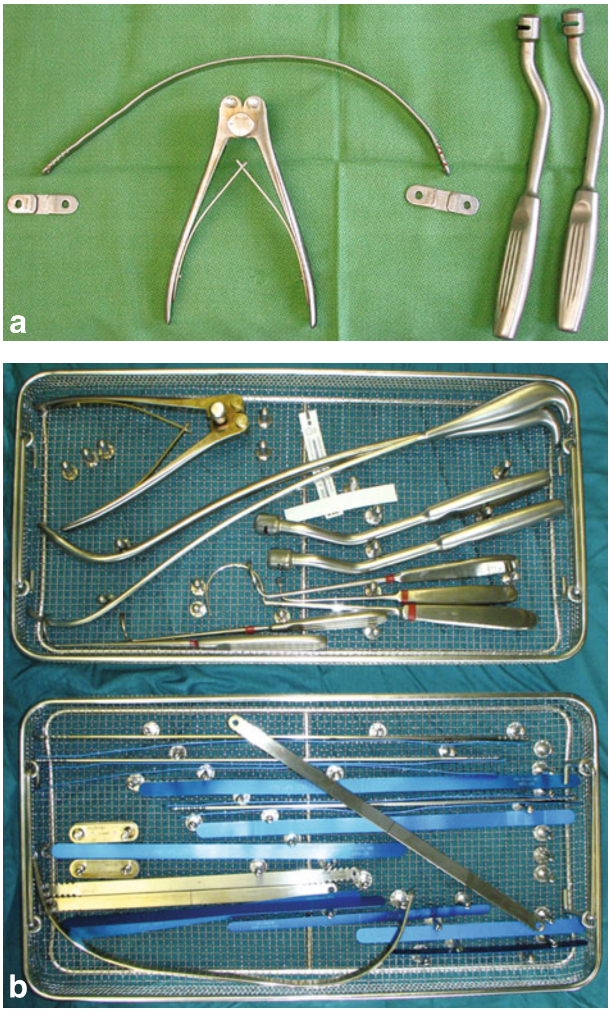


Fig. 2a and b. Standardized instruments for pectus bar implantation and explantation available from different manufacturers

of globalization it is to be hoped that the standard measures of the pectus bars and the relevant instruments (Fig. 2a and b) are furthermore retained uniformly within a consensus of different manufacturers and the applying physicians as well.

By this standardization on the other hand, boundaries within the use of these tools and materials are reached soon in the application in adults, because the material strength (thickness) of the pectus bar had been conceived and made just for the application in children. The massive pressure to the sternum in an exemplarily athletic adult with a deep funnel deformity therefore becomes too strong [9, 41]. Such differences in adults versus children have been measured and it turned out that the different load in athletic adults may reach 30-fold the load compared to a child [9]. It is therefore evident that even frequently suggested implantation of

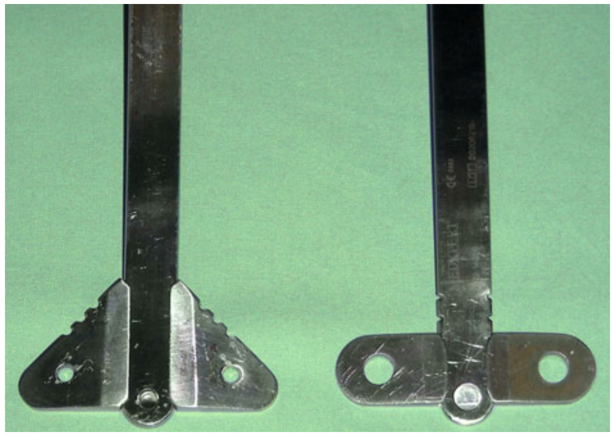


Fig. 3. Different shapes of lateral stabilizers, however fitting to the standardized pectus bars

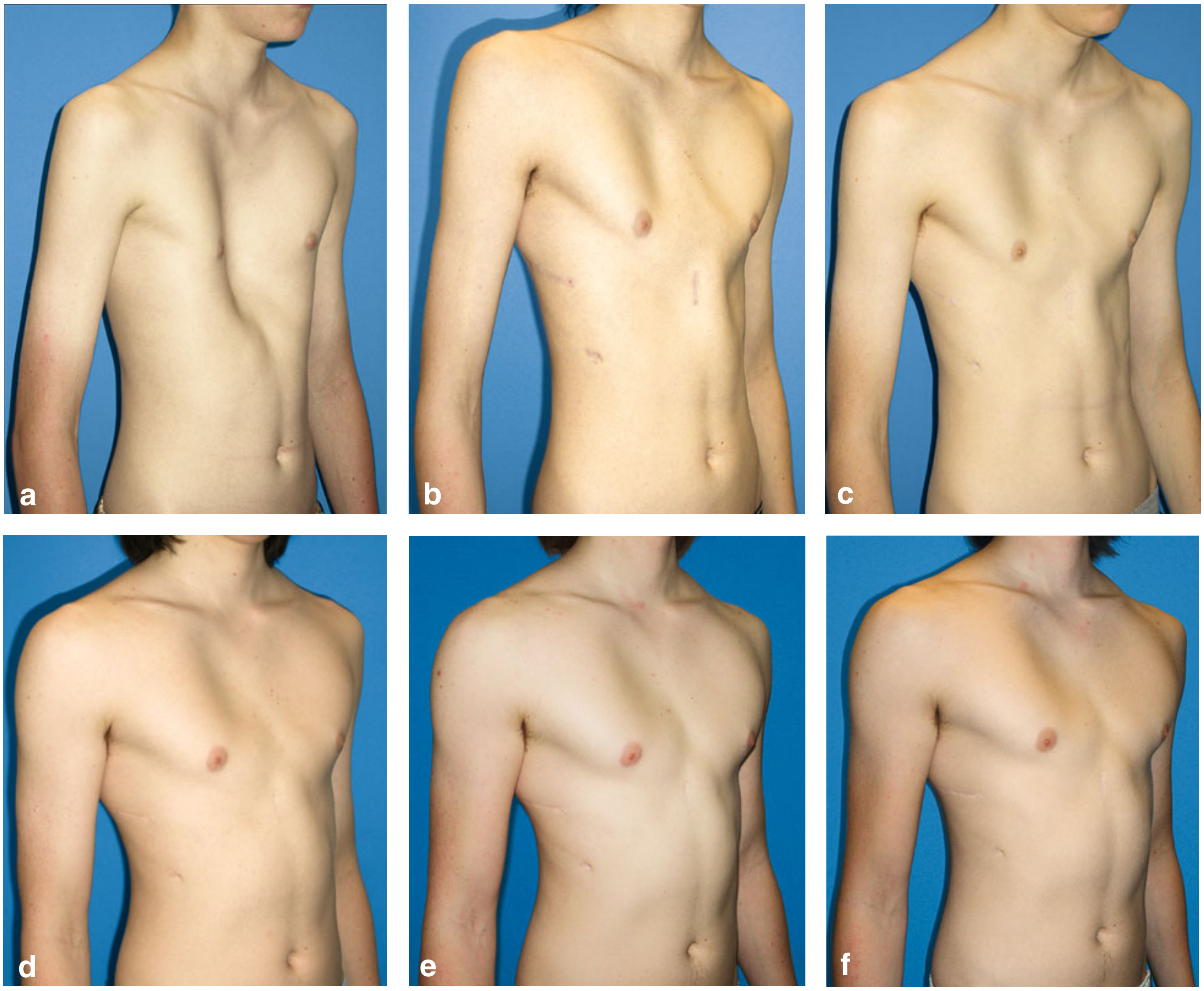
two pectus bars may rather not overcome the withstanding pressure from the rigidity of an adult anterior chest wall and other measurements have to be considered to alleviate that strain. In other words, the immense forces will be a subject of creating much more problems during surgery and postoperatively, in terms of difficulties of and during the surgical maneuver itself with increased rates of ensuing complications, whether immediately or later [8, 20, 22, 23]. The high pressure load focused at the back surface of the sternum on the one hand leads to partial unbending of the pectus bar in situ so that a major part of the supporting effect goes lost, if not primarily overcorrected. On the other hand, this unbending leads to sprawling of the bar wings laterally which cannot be prevented even with fixation techniques that use special stabilizers of different designs (Fig. 3). These laterally potentially projecting bar wings are then unpleasantly palpable (Fig. 19 in Chapter 12.1) and even well visible when attached with stabilizers. Moreover the high pressure on the vertex of the pectus bar leads to a pressure redistribution on the funnel margins and therewith onto the ribs, upon which the pectus bar rests. With such resulting high pressure load also at the back surface of the sternum and on the ribs, it becomes intelligible that pains are increased and therefore complained much more by adults than by children. Therefore, the MIRPE method was modified to use even two pectus bars for the purpose of load distribution [5, 23]. This modification has proved to be advantageous in certain indications such as a wide and flat funnel deformity, asymmetry [29], steep and deep funnel depressions; however it tends to create more complications yet [9]. Arrosion of the bony integrity of sternum or ribs with pathological fractures (Chapter 12.1), a prolonged pain symptom complex, and other consequences of such an expanded surgical manipulation are possible sequelae. These include increased risk of intrathoracal organ injury, increased inclination to pleural effusion, hematoma, or infection through an extended thus tissue damaging surgical access.

With all these and possibly other problems a surgeon is confronted, who tries to adapt this technique, which was primarily developed for children, unreflected to adults. The original MIRPE technique is extremely suitable for children and herewith already established for many years now [31]. If utilized in grown-up patients with much more matured and strengthened body, it will evidently bear more risks for complications or an undesired outcome [20]. Though being unprepared to and unaware about a totally altered anatomical and functional situation with different strengths of withstanding forces to remodeling attempts, such surgery might become a cumbersome endeavor. The overall biomechanics and possible compensation mechanisms basically differ from those in children [9, 31]. It is therefore unavoidable that in the initiation phase to apply the MIRPE also in adults, several shortcomings are made, furthermore particularly solely with adults no evidence-based reports of experiences with larger series and consistently selected patients yet exist.

However and on the other hand nowadays it is no longer possible to design prospective comparative studies between conventional techniques and the MIRPE technique [24]. Patients on the basis of their knowledge and the resulting prejudice, which is propagated by many media, can no longer be randomized and distributed into groups. The gain of experience often relies only on results obtained by individual case series published with short-term results only and anecdotical transmission of tips and tricks, however also experienced pitfalls. Several institutions perform corrective surgery but each with a variety of techniques, different surgeons, and overall within a collective of patients with inconsistent age, body shape, and extent of deformity. Therefore, no sufficient level of scientific evidence based on randomized controlled trials is available for the selection of individual proper treatment, especially for the treatment in adults. With increasing pressure through those who usually know well about case stories informed patients and probably increasing security in managing the peculiarities of the treatment in adults using the MIRPE technique, more reports containing larger series [15, 24] will hopefully become available. Equally long-term observations several to many years after the removal of the pectus bars are necessary to prove the benefit of the technique in adults too (Figs. 4a–g and 5a, b). The gain of experience in adult patients is still positioned in the status of a work-in-progress. On the basis of lacking and secured results with long-term observation at the current moment, one cannot yet state with certainty that the MIRPE technique applied in adults will provide equal success as that in children and adolescents, although several purely technical notes and reports with good results after short-term follow-up are already available, however already pointing out particular difficulties concerning technique and complication rates [20, 22, 23, 27, 28, 30, 35, 42].

Also the factor of yet ongoing growth before reaching adulthood still has an important influence on the success of the MIRPE. Its effects on the chest wall guide the remodeling process by a pectus bar during childhood and substantially better in adolescence. The conversion forces from cavity to convexity at the sternum and adjoining ribs by the pectus bar should be set at a time that transmission of forces is accompanied by skeletal growth. As such biodynamics through guided growth by the pectus bar over years lead to a stable formation of the anterior thoracic wall. Such a guided shaping evidently should lead to stagnation of any remodeling forces after maturation of body growth. Therefore even after removal of the pectus bar sufficient rigidity has developed and no further disfiguring growth of rib cartilages may occur. Just these biomechanical considerations now vote for putting the surgical correction of asymptomatic funnel chest deformities by MIRPE into puberty, on the one hand in order to utilize guided chest wall formation through finalizing maturation growth and on the other hand in order to obtain also a stable and therewith durable result.

Under these aspects, the use of MIRPE appears rather inopportune at the adult skeleton because no shaping growth guided by hardware takes place any more. The realization of conversion from a cavity to arching herewith is managed through the pressure of the pectus bar to the sternum. In analogy to osteodistraction, an osteo-chondro-distension of the anterior thoracic wall takes place. Such forces considerably necessary in tall or athletic adults can hardly be held by a single pectus bar. Occasionally a second pectus bar is sufficient, but at times even that modification will not suffice to withstand the biomechanical forces caused by rigidly disfigured anatomy. This problematic nature is the more stronger and steeper the funnel deformity is, the more athletic and older a patient is. The pure MIRPE yet can be the method of choice in a 35-year-old slim woman (Chapter 9), but can present a contraindication in a sportive 20-year-old fellow, on the basis of complications to be ex-



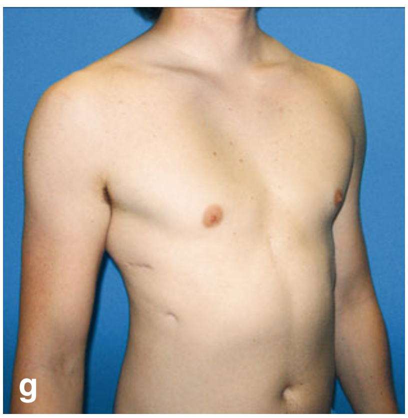


Fig. 4. Series of a long-term follow-up in a 15-year-old male, preoperatively (**a**). Six months postoperatively after MIRPE with one pectus bar (**b**). After 1 year (**c**). After 2 years (**d**). After 3 years (**e**). After 3 years and 10 months, prior to pectus bar removal (**f**). One year after pectus bar removal, at an age of 20 years (**g**)

pected due to biomechanical strains through muscular tightness and skeletal rigidity.
In such cases inappropriate for the MIRPE a modified combined access with osteochondrotomies performed via additional surgical access may be better suitable. The pectus bar implantation is supported through a complementary central access at the submammary or parasternal area to perform a horizontal sternotomy at a level more cranially, with or without parasternal chondrotomies or chondrectomies, according to the method

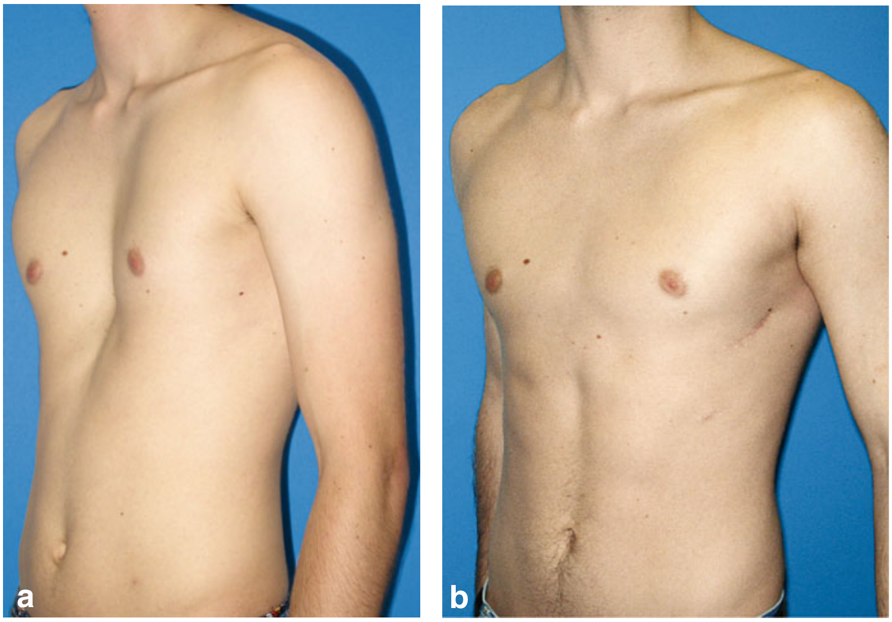


Fig. 5. 19-Year-old male with moderate funnel chest deformity, planned for MIRPE with one pectus bar (**a**). Situation 3 years after pectus bar explantation with very pleasing result, now 6 years after initial surgery (**b**)

of Ravitch (Chapter 6.1). Al-Assiri in 2009 noted in a comparative study, however in a collective of children, that the addition of sternocostal relaxing incisions to the standard Nuss procedure appears to facilitate retrosternal dissection and bar placement [1]. However, there were no changes in long-term function or cosmesis notable. The use of relaxing incisions also in children appears to be safe and may facilitate operative visualization of retrosternal structures. This concept of relaxing incisions but with additionally required chondrectomies in the rigid adult skeletal structures seems to expand the feasibility of minor invasive remodeling of the anterior chest wall to mature bodies in adults and athletic or tall patients within adolescence likewise.

6.4.1 Surgical technique with the modified hybrid access in adolescents and adults, the MOVARPE (Minor Open Videoendoscopically Assisted Repair of Pectus Excavatum) technique

The initial steps of surgery in the MOVARPE technique are the same as in the MIRPE technique (Chapter 6.3), but hybridized with additional incisions and remodeling interventions according to the combined technique published by Jensen in 1970 [17]. Bilateral incisions expose the serratus anterior muscles, their slips are bluntly separated with utmost care not to damage the lateral thoracic nerve. The undersurface of the serratus muscle interdigitating with the pectoralis major muscle is dissected free from the chest wall and a tunnel until the funnel rim medially as well as a pocket for the bar wings

Fig. 6. Intraoperative situs showing the surgical incision placed along the submammary crease for the purpose of sternotomy using an angled saw and a specially designed retractor ready to fix a cold light source for better survey underneath the elevated skin

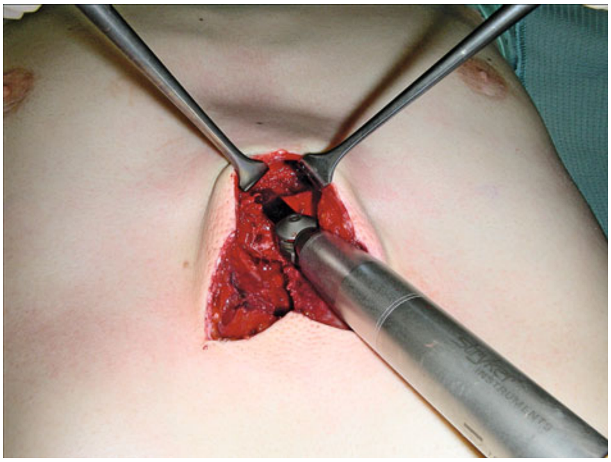


Fig. 7. Procedure of sternotomy in a male patient via a presternal incision

laterally is created. The incisions always follow the RSTL especially in the additional incisions at the anterior thorax. Here the incisions (Fig. 6) are placed near the planned relaxing chondrotomies and within a distance by which the sternotomy may be accomplished within a subcutaneous tunnel using an angled saw (Chapters 9 and 13.2). The pectoralis major muscle flaps may be raised or preferentially dissected in the muscle split technique to reach the individual ribs for chondroplasties [36]. Severely distorted rib cartilages are resected subperichondrially, whereas minor deformations are corrected by wedge resections or incisions just for weakening the continuity or relaxing the distorted arches of the ribs. The sternotomy (Fig. 7) is also performed as a wedge resection to create a small gap that enables elevation of the mobilized central thoracic wall unit. In symmetrically developed funnels, the osteotomy does not include the posterior table of the sternum in order to prevent dislocation by mobilization. Solely in the cases with malrotation of the sternum, the osteotomy has to be performed as a complete transsection to allow derotation of the sternum into a frontal plane. Either using a bone hook or using the finger after blunt separation of the pleura and pericardium from its back side, the sternum is elevated [17], causing intentional green-stick fracture of the posterior table of the sternum, if not totally transsected otherwise for the purpose of sternum derotation. Now the endoscopic ports are placed at the anterio-lateral chest wall about two or three intercostal spaces above the lowermost ribs and rib arch (Fig. 8). The tunnelizer under videoendoscopic view and deflation of the right lung (double lumen intubation,

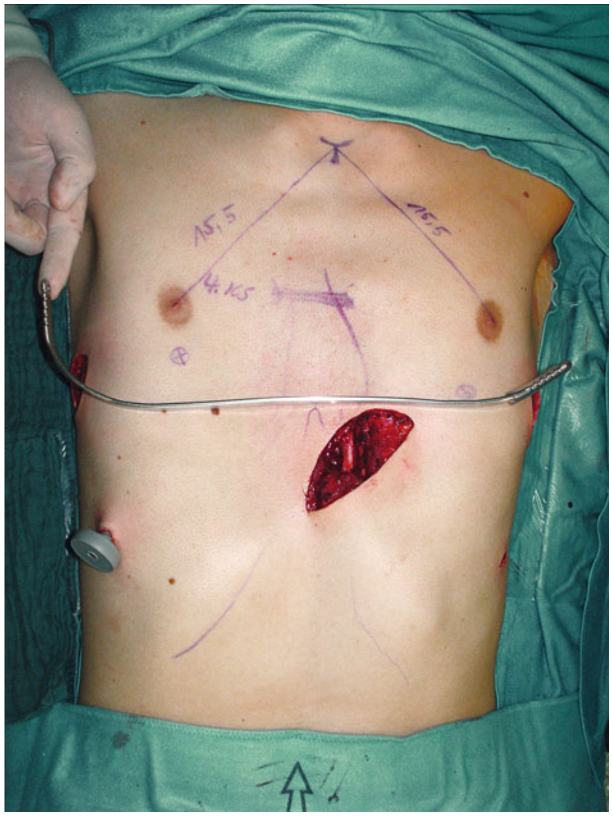


Fig. 8. Intraoperative view with already performed relaxing sternochondroplasties via the left parasternal incision. The shaped pectus bar placed into the desired direction above the skin. The endoscopic ports placed at the lower rib arches, ready for insertion of the endoscope

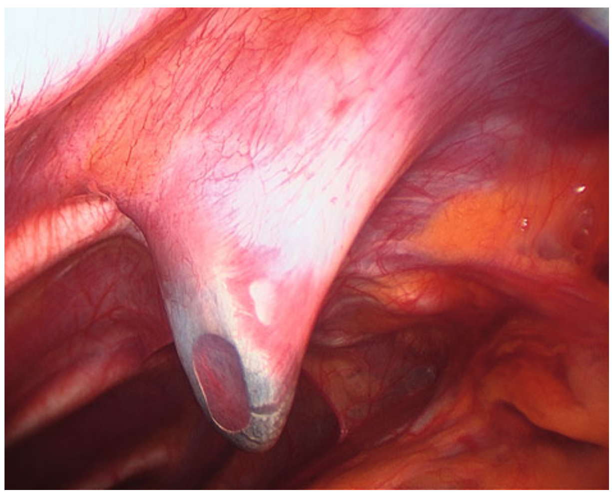


Fig. 9. Endoscopic view into the right thoracic cavity with the tip of the round tunnelizer entering the thoracic cavity prior to perforation of the parietal pleura

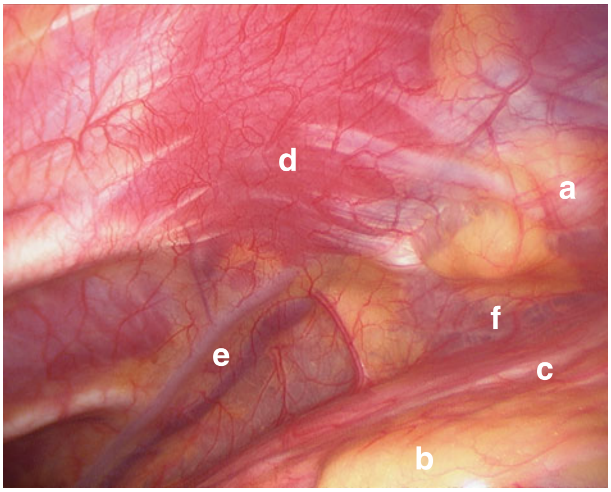


Fig. 10. Endoscopic view with posterior aspect of the right parasternal chest wall. (*a*) Sternum depression, (*b*) pericardium, (*c*) phrenic nerve, (*d*) transversus thoracic muscle, (*e*) internal thoracic (mammary) vessels, (*f*) point of retrosternal passage of tunnelizer and pectus bar

Chapter 5.3) now perforates the intercostal muscles and pleura to reach the thoracic cavity (Fig. 9). With simultaneous elevation of the mobilized anterior chest wall the tunnelizer is gently pushed versus the midline with particular caution to the heart, the phrenic nerve, and the internal thoracic vessels (Fig. 10). The chest wall elevation now alleviates the passage of the instrument (Fig. 11a) behind the sternum and in front of the pericardium [1, 5]. During that maneuver, the introduced finger simultaneously to visual control may guide the tip of the instrument between the mediastinal organs and the sternum (Fig. 11b and c). Under alternate insufflation and deflation of the lungs, the procedure is proceeded at the left throacic cavity again under visualization by the videoendoscope (Fig. 11d and e); the thoracic wall is perforated within the rim of the funnel likewise to the contralateral side. Due to the rigidity of the thoracic structures rupture of the intercostal muscles beyond the funnel rim caused by undue shoving and leverage forces of the tunnelizer means a probable technical failure. Furthermore such surgical violence will disrupt intercostal muscles from the ribs, either causing large holes in the pleura or causing immediate dislodgement of the pectus bar to dorsal, along the course of the ribs. Concomitant complications such as pneumothorax, wound infection, and late sequels like bar dislocation, and reduced respiration capacity by scarring or migration of the pectus bar into the thoracic cavity may occur (Fig. 17 in Chapter 12.1). That is why a rounded tunnelizer without edges is preferably used to avoid shearing-off effects (Chapter 13.2). The shaped pectus bar intraoperatively is fixed to the tunnelizer with a strong suture (e.g. Mersilene® strap), lubricated with gel, and then implanted in a reverse way. This maneuver is again performed under alternate ventilation, elevation of the anterior chest wall, and permanent visualization by the endoscope (Fig. 12a–f). After implantation, the pectus bar is tilted with the flipper instruments along its own axis to its definite position, with the bar wings placed into submuscular pockets at the lateral thoracic wall. Final inspection of the thoracic cavity by endoscope is done prior to wound closure (Fig. 12f). The bar wings are fixed with several circumcostal PDS-sutures (Fig. 13a–e) in order to avoid displacement [13, 39]. By the paramedian access, a third fixation parasternally but lateral to the internal thoracic vessels is feasible and recommended to prevent dislocation (Fig. 13f). During suturing the deep wound layers, the anesthesist is requested to raise the PEEP to extrude remaining air from the pleural cavity via the endoscopic ports until final skin closure. Commonly no chest tube then is necessary, although in most of the cases [4] a sickle-shaped small but asymptomatic pneumothorax is recognizable, which usually dissolves within a few days. Postoperative X-rays are recommended during the stay to exclude pneumothorax, hemorrage, or pleural effusion (Fig. 14a and b).

In summary, the main advantage in the application of a hybrid technique consists of the advantages of the rapid and elegantly performable MIRPE conjoined with parts of the conventional Ravitch procedure to allow a remodeling procedure without tension and stable support of the elevated anterior chest wall. Besides that, postoperative pain episodes are diminished by the fact that lever forces of the pectus bar versus the sternum are reduced by such additional relaxing and mobilization maneuver. On the other hand, the time needed for pectus bar support until healing of sternotomy and chondroplasties is notably reduced down to 1 year versus the period of up to three or more years in the chest wall distension technique of MIRPE. The surgical access to the sternum with relaxing osteotomy and parasternal chondroplasties allows stable scarring already after several weeks, supported by a pectus bar for 1 year then to enable further rigid healing. Such a formation of callus in the area of the sternotomy by secondary bone healing after few months sufficiently

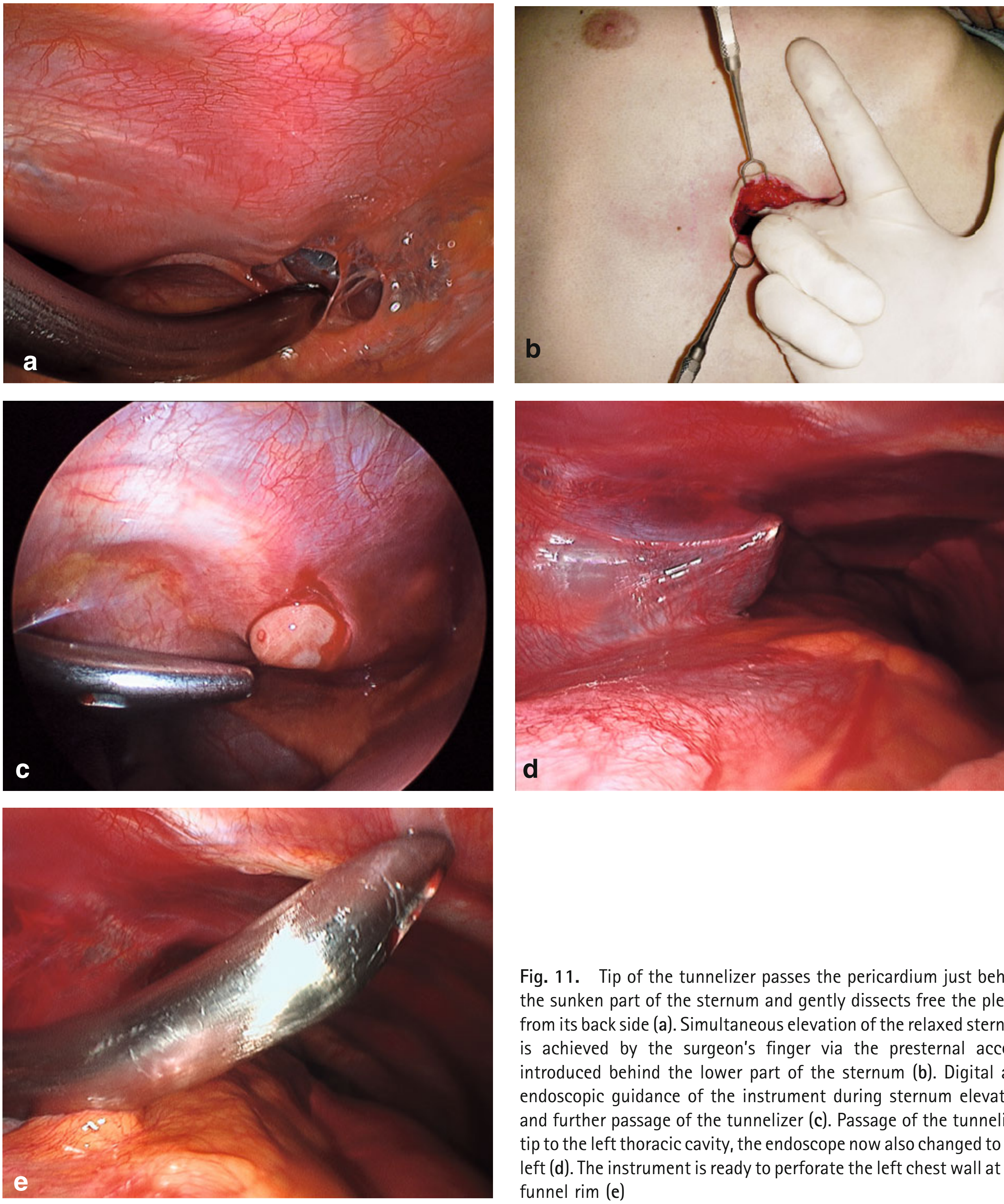


Fig. 11. Tip of the tunnelizer passes the pericardium just behind the sunken part of the sternum and gently dissects free the pleura from its back side (**a**). Simultaneous elevation of the relaxed sternum is achieved by the surgeon's finger via the presternal access, introduced behind the lower part of the sternum (**b**). Digital and endoscopic guidance of the instrument during sternum elevation and further passage of the tunnelizer (**c**). Passage of the tunnelizer tip to the left thoracic cavity, the endoscope now also changed to the left (**d**). The instrument is ready to perforate the left chest wall at the funnel rim (**e**)

allows permanent stability then (Figs. 15a–b, 16a, b and 17a–f).

The extension of the MIRPE to a MOVARPE technique in adults on the other hand increases the surgical expenses and furthermore the operation time by approximately up to an hour. An additional disadvantage is the need for one or two separate skin incisions, creating further scars. However,

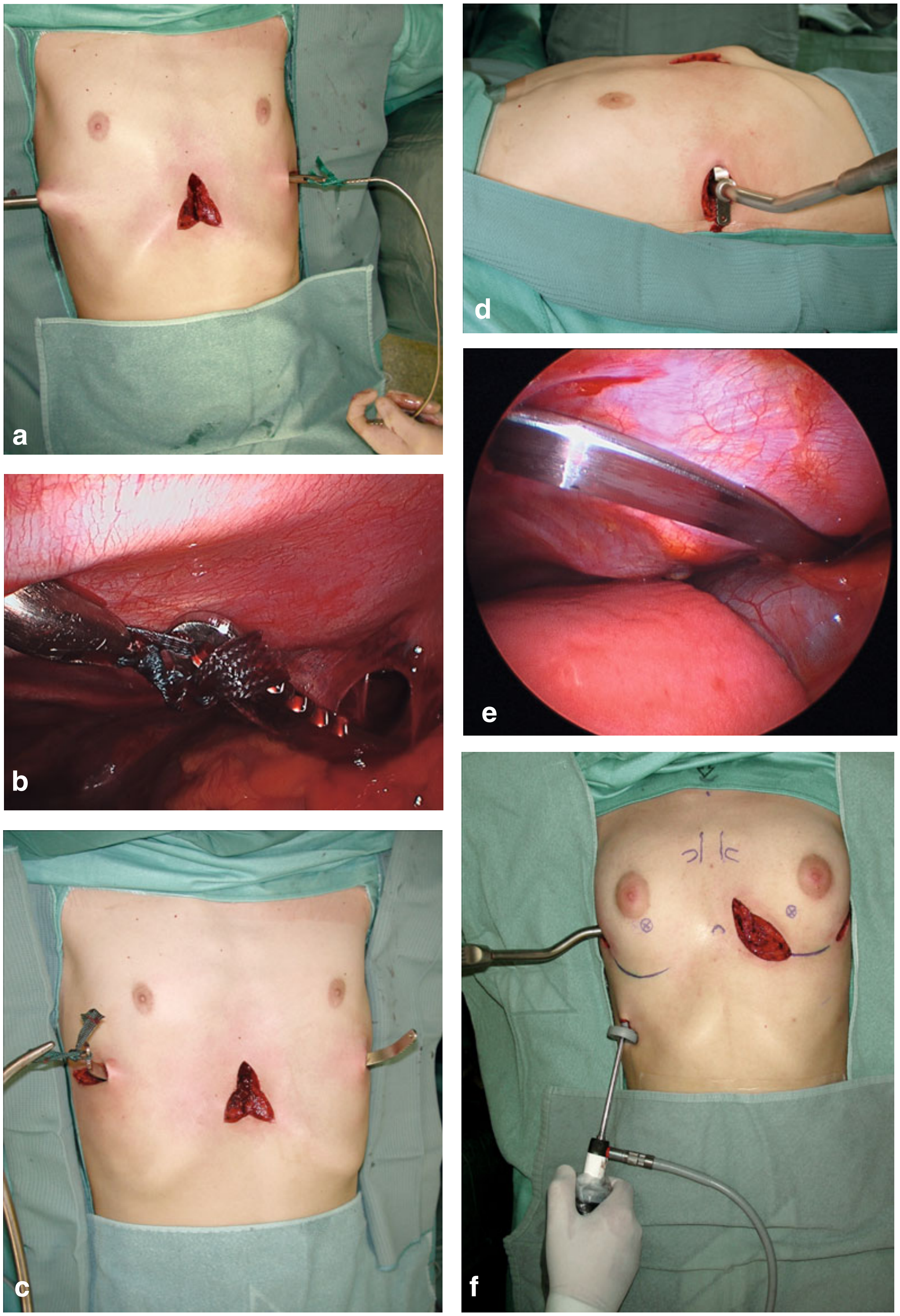


Fig. 12. Tunnelizer in place, the shaped pectus bar is fixed to the tunnelizer with a strong band (**a**). Endoscopic view into the right thoracic cavity, the pectus bar hitched to the tunnelizer already passed the left thoracic cavity, the retrosternal area, and pericardium, prior to emerging through the right chest wall (**b**). Passed pectus bar, still being tilted up prior to twisting it along a transversal axis (**c**). Utilizing the flipper instruments to twist the pectus bar at 180° and to place it into its desired final position (**d**). The pectus bar seen from the right thoracic cavity with apparent lever pressure against the posterior surface of the sternum (**e**). Inspection of both thoracic cavities after pectus bar tilting into its final position using the endoscope to exclude any unintentional trauma or complications (**f**)

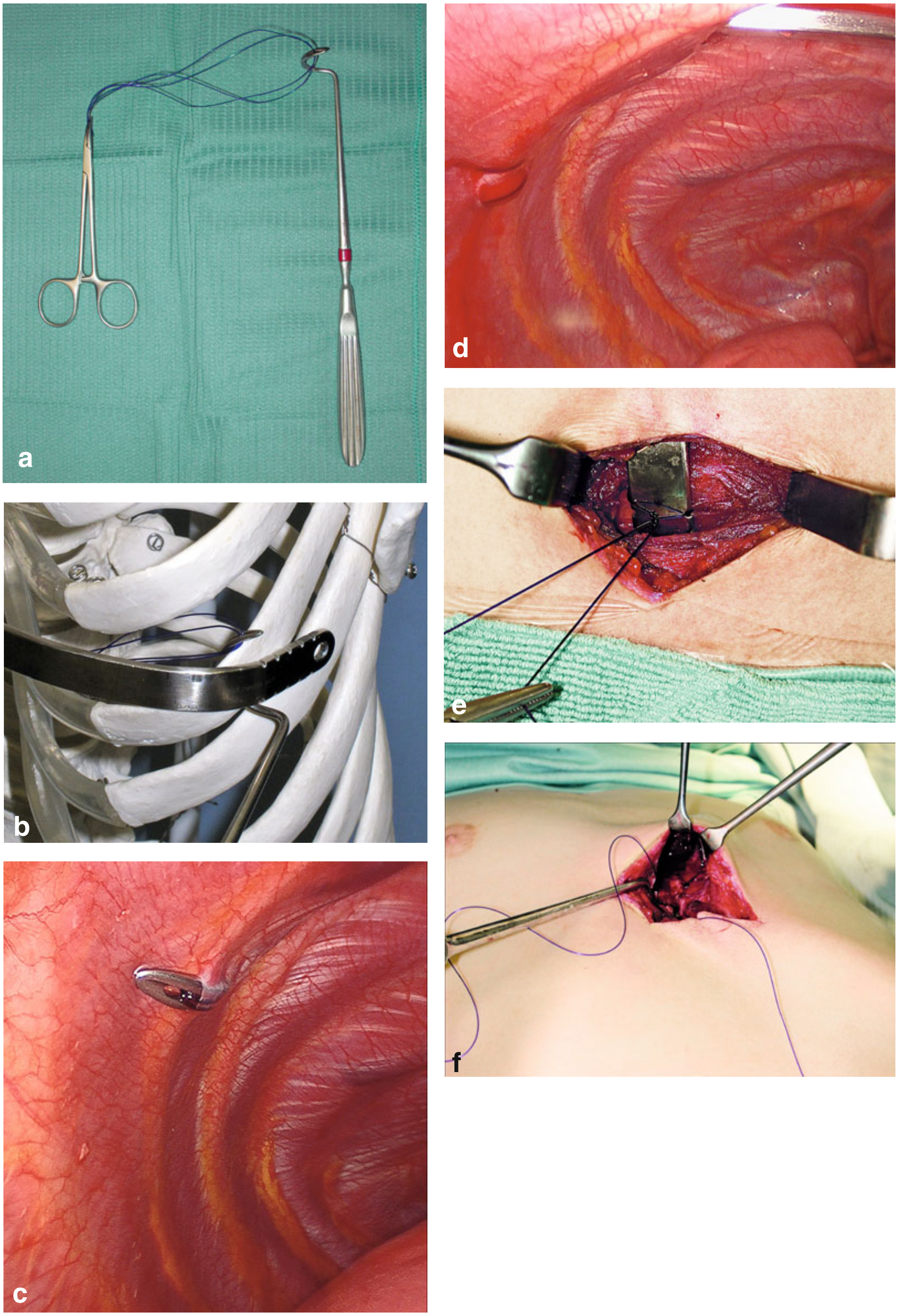


Fig. 13. Deschamps needle armed with PDS suture (**a**). Schematic depiction how circumcostal suture is placed with Deschamps needle and fixes Pectus bar wing to the rib to avoid tilting (**b**). Endoscopic view at the right lateral thoracic wall with invading tip of Deschamps needle, closely passing around the rib (**c**). Final situation with fixed suture (left) and pectus bar (above) in place (**d**). View at lateral incision and wing of pectus bar with circumcostal suture (**e**). Parasternally placed (three-point) suture for additional security against dislocation of the pectus bar (**f**)

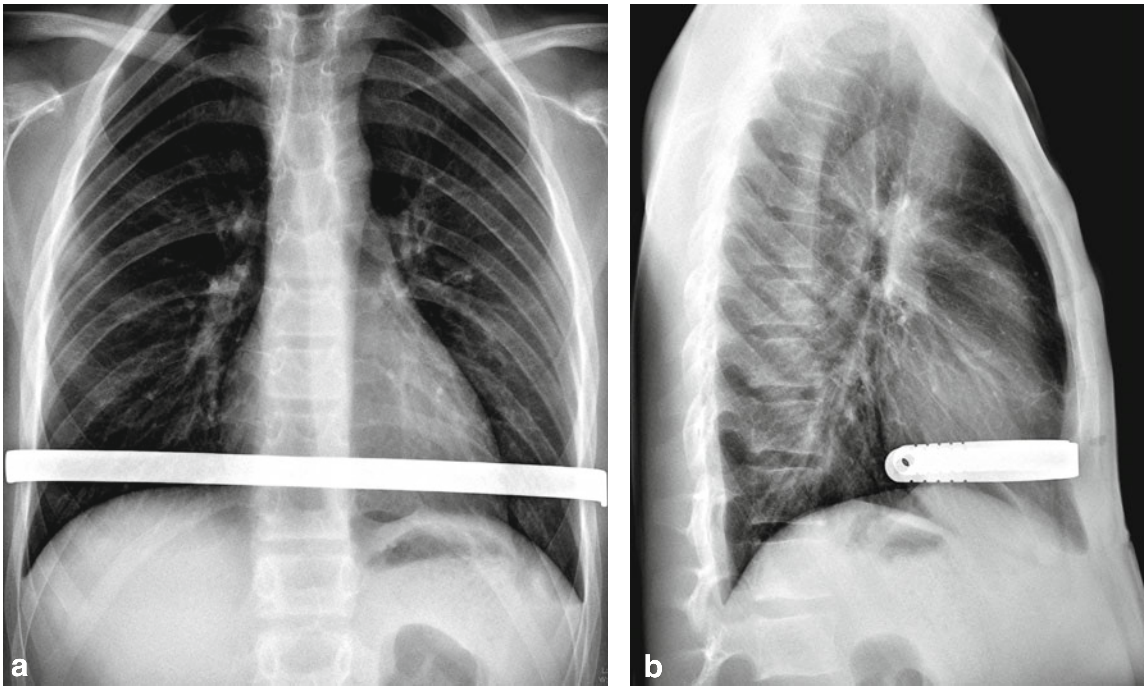


Fig. 14a and b. Postoperative X-rays with perfectly placed pectus bar, without hemothorax, hemorrage, or pleural effusion

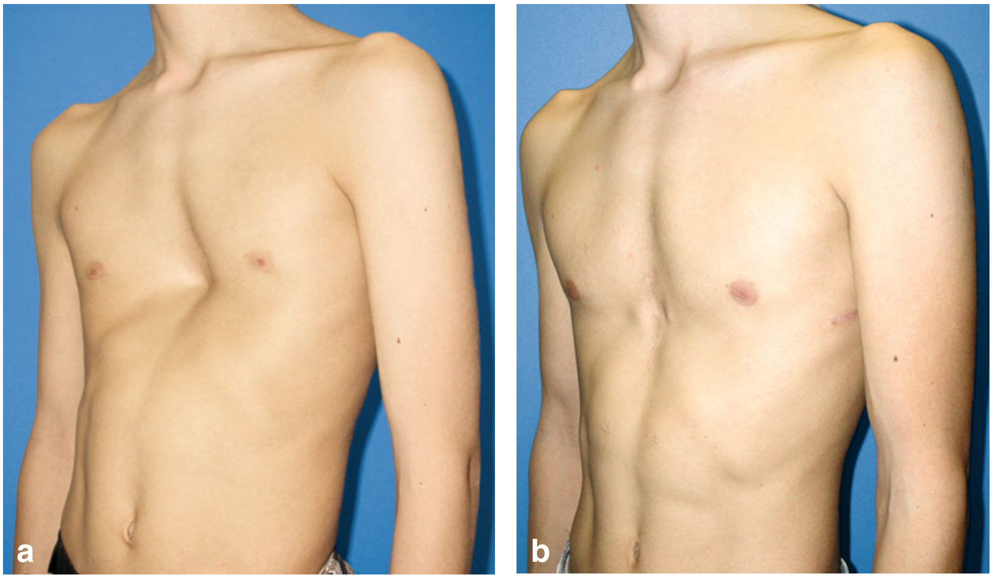


Fig. 15. 16-Year-old male with severe pectus excavatum deformity, psychic alteration, and moderate cardiopulmonal restriction (**a**). One year after explantation of the pectus bar, 2 years after initial surgery (**b**)

these scars may be placed distant from the midline and especially in females (Chapter 9) may be placed very well hidden along the inframammary crease (Fig. 12f).

6.4.2 Discussion

Results with the MIRPE in adults may be presented as good and excellent in so far available publications of

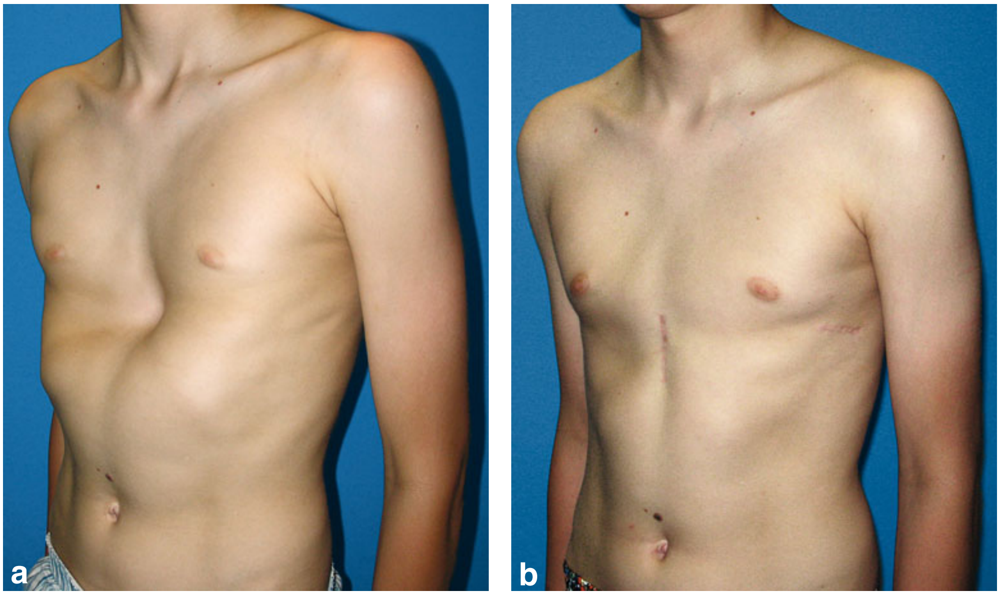


Fig. 16a. 15-Year-old male with severe funnel chest deformity but absence of function impairment. **b** Situation 1 year after pectus bar removal and 30 months after initial hybrid MOVARPE surgery

larger series in the Asian population [2, 5, 18, 22, 23]. However, it must be taken into consideration that Asians usually have a more asthenic physique than exemplarily Europeans. Weight over 90 kg and tallness above 190 cm in adolescents or adults within the caucasian race presenting with pectus excavatum are not rare incidents. The average physical characteristics of caucasian population with or without chest wall deformities usually lie far from those in the Asian population. That is why relevant publications with good outcome series in Asian adults [18] may not be simply transmitted without reflection to different biomechanical properties of the body and skeleton within different races. Leonhardt in a series with MIRPE in 48 European adults in 2005 pointed out that adults with severe or asymmetric deformities are at a greater risk of recurrence after a Nuss repair, thus 27% of these patients had to undergo reoperation with a Ravitch technique for finally content reshaping [20].

These findings in Europeans suggest that a hybrid technique using the MIRPE conjoined with partitions of the Ravitch procedure as the so-called MOVARPE technique will increase the general beneficial outcome when applied in adults. Until now, at our institution 21 selected patients (Fig. 18a–c) with a mean age of 24, 8 years underwent a hybrid repair of pectus excavatum and so far no patient required reoperation; minor relapse of sunken sternum (0.5–1 cm) was apparent in 4 patients only after pectus bar removal (Unpublished data, 2009).

6.4.3 Final comments

The MIRPE due to several advantages remains as the ideal therapeutic option in childhood and adolescence [4, 26], even in selected cases in adulthood. Nevertheless the more rigid and more severe the deformity appears beyond puberty, the hybrid technique MOVARPE seems to represent an alternative method with lesser pain periods, lesser pectus bar implantation period, and a lower rate of common complications, to be noted at first a tilting of the bar.

Above all in extensive pectus excavatum deformities at a higher age, also in existence of systemic diseases like Marfan syndrome or previous operations at the thorax, for surgeons of different disciplines it is very advisable to carry out indication setting and surgery as an interdisciplinary treatment jointly with thoracic surgeons experienced with that manner and potential intrathoracic complications.

Furthermore the indication for minimally invasive (MIRPE), minor open (MOVARPE), or conventional invasive surgery (Ravitch) at a body unit functioning for breathing must carefully outweigh the advantage of a psychological benefit.

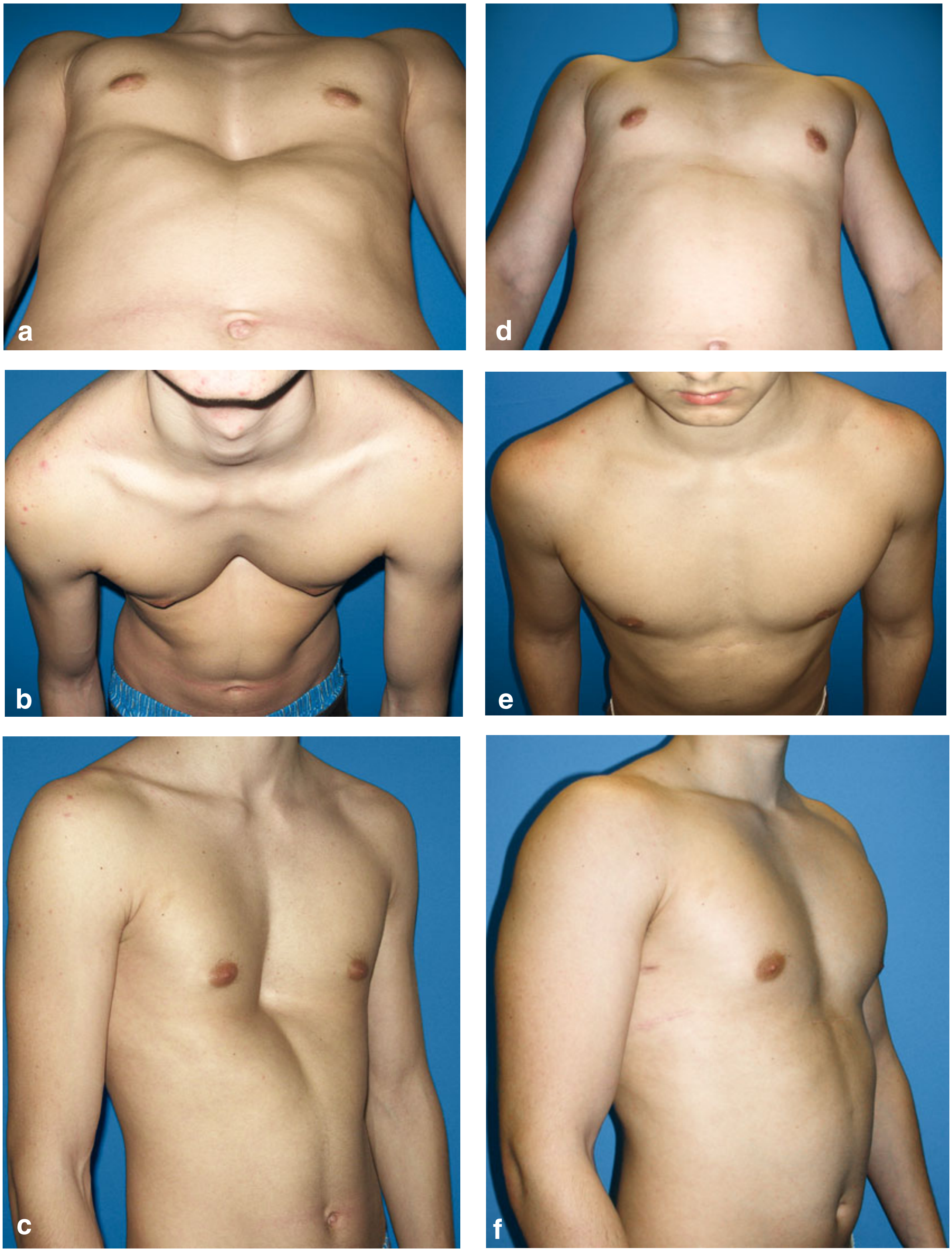


Fig. 17. 18-Year-old male with marked deformity and very rigid thorax (**a–c**). Situation 3 years after initial hybrid MOVARPE surgery. The patient refused removal of the pectus bar planned 1 year after implantation, it was finally removed after 3 years (**d–f**)

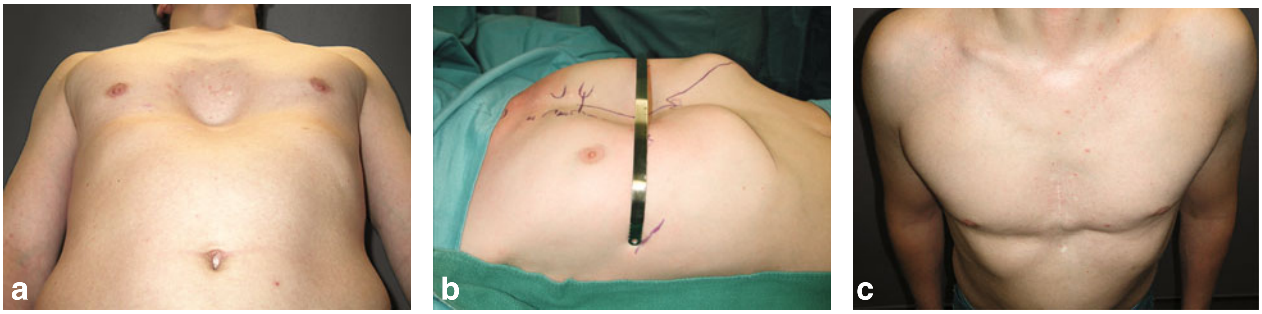


Fig. 18. 45-Year-old male with increasing cardiopulmonal impairment thus definite indication for anterior chest wall repair (a, b). Situation 1 year after pectus bar removal and 30 months after initial hybrid MOVARPE surgery (c). The cardiopulmonal function markedly increased

Surgeons taking care of adult patients also should be cognizant of all treatment modalities up-to-date and each intervention must be carefully selected and tailored to the individual patient.

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6.5 Custom-made silicone implants

Anton H. Schwabegger, Barbara Del Frari

6.5.1 Introduction

The method of simple implantation of a prefabricated, so-called custom-made implant made of silicone rubber has tradition since several decades already [1] especially for those cases, where a pure aesthetic improvement of the deformity in adults was aimed. In the seventies and eighties of the last century the development of an at room temperature vulcanizing [2–4] so-called RTV 382 silicone led to very pleasing aesthetic results with only one advantageously minor intervention and long-lasting results. That RTV silicone was implanted as a device vulcanized 24 h prior to surgery or as a viscous liquid component that vulcanized (polymerized) into a solid though elastic block in situ, within a dissected subcutaneous tissue pocket. By that and prior to the polymerization process in situ, the silicone temporarily contained viscous properties for some minutes, so that it was still feasible to perform simple manual contouring in situ with respect to the intended form and extension of the dissected subcutaneous pocket. The process of polymerization however, produced unpredictable reactions at the skin and subcutaneous tissue and thus was banned by the US government in the early eighties. Pretty often these implants nowadays, after two to three decades of unproblematic course, are removed due to calcifications within the tissue capsule and subsequent chronic seroma formation (Figs. 1–3). In the few cases of our own series of explantation however, no capsular contracture was found upon exploration during explantation. These implants still present themselves as pliable and soft like rubber gum (Fig. 4a, b). Due to the development

Fig. 1. Chronic seroma with reactive skin irritation lasting for over 4 months, 23 years after implantation of a RTV 382 at room temperature vulcanizing silicone for a pectus excavatum deformity. Bulging deformity and pain now indicated removal of the implant

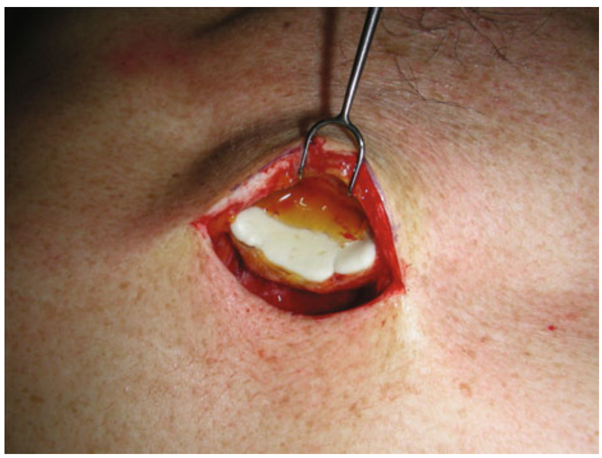

Fig. 2. The situation upon surgical exploration, the implant almost entirely floating in microbiologically diagnosed sterile seroma within the already opened fibrous capsule

Fig. 3. Tissue pocket after explantation of the whole implant depicting the capsule with calcification plaques (yellow) along most of the inner surface of the capsule

of prefabricated silicone implants, the utilization of that polymerizing silicone was abandoned soon thereafter. Nowadays, after several steps of technical improvements these implants are available and readily used [5–7], either solid and inflexible on the one hand, or very soft and pliable on the other hand, whether with smooth or textured surface (Fig. 5), with or without fixation tongues. Alternatively to such tongues, multiple holes may be cut into the implant using a surgical rongeur, enabling ingrowths of granulation and subsequently scar tissue, which provides with tight fitting and avoidance of dislocation (Fig. 6a, b).

Nowadays the technique of utilization of prefabricated or so-called custom-made silicone implants is very effective, minimally invasive and safe, with reproducible long lasting good to perfect aesthetic results and commonly very high patient satisfaction [8, 9]. It is a useful technique for the adult patients when growth has

Fig. 4a. Anterior surface of the explanted RTV 382 silicone, same patient as in Figs. 1–3. **b** Posterior surface of the explanted RTV 382 silicone, same patient as in Figs. 1–3

Fig. 5. Custom-made modern silicone implants of various size, the upper right and the lower left with different kinds of textured superficial structure, the other implants show smooth surfaces

already finished (Figs. 7 and 8) and for patients with only a mild expression of the pectus excavatum deformity [7, 8, 14, 15] and particularly in patients with a Poland syndrome (Chapter 10.1). It is ideally suitable for asymptomatic patients with sternal depression but without cardiopulmonary problems [10].

Though, it must be taken into account, that after implantation of a moderate or unfavorable large-sized silicone block, a cramping anatomical deformity will not be corrected but even may aggravate the subjective feeling of cramping. This foreign body encumbering the sternum, if too large and heavy in weight, will soon be condemned by the patient with the need of removal as a consequence.

However, custom-made silicone blocks are not sufficiently effective for highly deformed funnel chests and cannot correct the underlying structural defect with its associated functional problems. This means that this procedure leaves the physical condition absolutely unimproved, but may even deteriorate it due to psychologically triggered feeling of cramping by the weight burden of the implant upon the sternal region. The simple aesthetical correction of an extensive funnel chest without consideration of a functional rectification on the other hand may leave a problematic situation for these particular patients.

6.5.2 Fabrication of the implant

For the manufacture of the custom-made silicon implant a precise mold of the funnel depression must be made. For that purpose a special kit (Moulage Kit; McGhan Medical Corporation™, Santa Barbara, CA, USA; Fig. 9) is available. The mold alternatively may be made of different kinds of materials, like dental alginate [7], wax or plaster of Paris. This mold is manufactured in the surgeon's outpatient office, with the

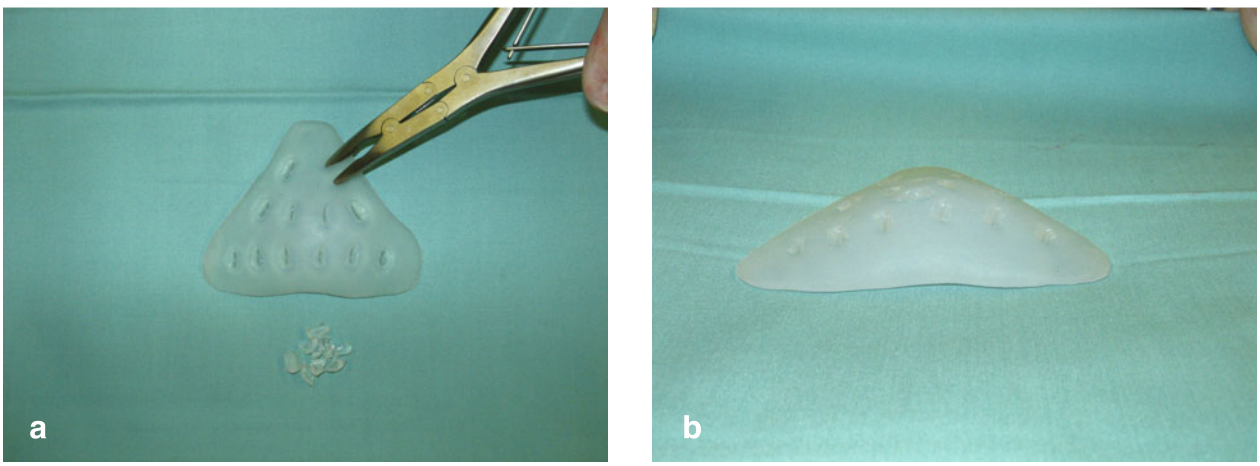

Fig. 6a. Custom-made implant during surgery, cutting holes into the implant to allow tissue ingrowths for stable and permanent fixation to the surrounding tissue. b Oblique aspect of the prepared smooth and textured silicone implant


Fig. 7a. Frontal oblique view of a 23 years old man with symmetrical pectus excavatum. **b** Result of the same patient 6 months postoperatively

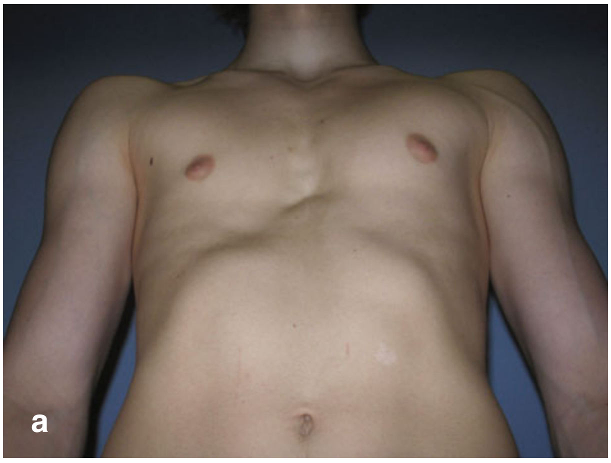
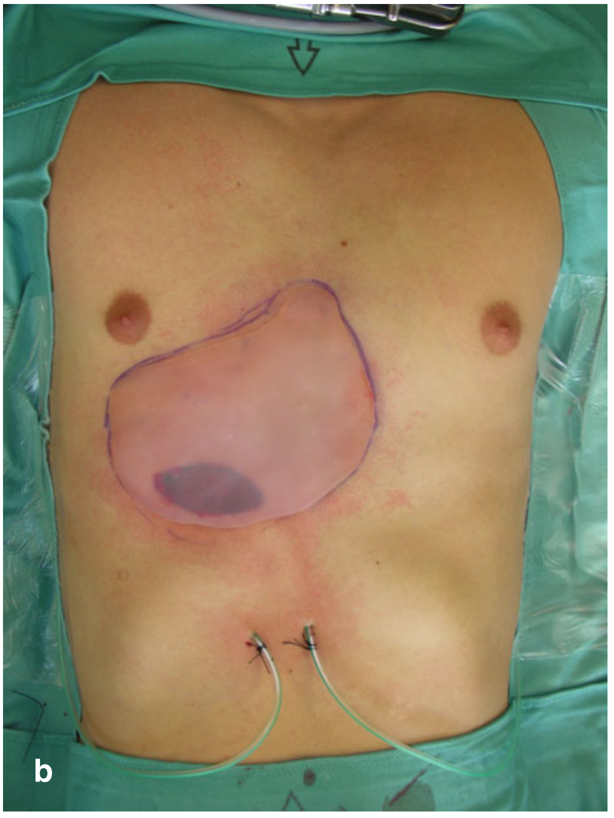


Fig. 8a. Preoperative situs in a 16 years old athletic male with asymmetry, markedly at the left side. **b** Intraoperative situs with the implant placed above the already dissected pocket. Notice the small skin incision behind the implant, sufficiently large for the passage of the folded implant and placed horizontally along the RSTL. **c** Situation 1 year after surgery with high contentedness of the patient

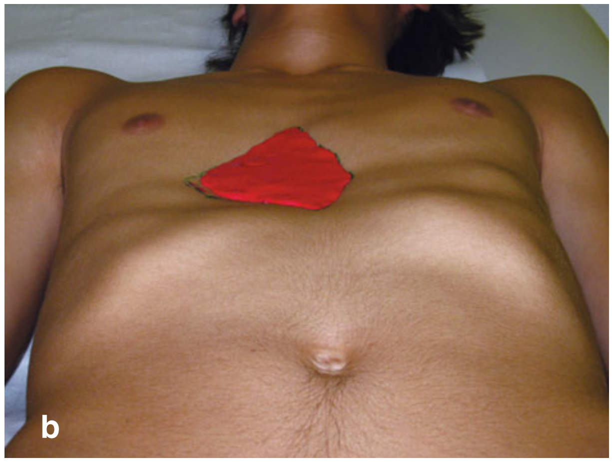

Fig. 9a. Exemplary moulage kit with the two components to be mixed manually. Depending on the exact percentage of the two components the vulcanizing time may last between few to many minutes, which allows secondary corrections after application to the patient's body. At the right side cube samples of available different softness qualities are depicted. XS, extra soft; S, soft; M, medium; F, firm. **b** Moulage adjusted but still soft in situ, waiting for vulcanization at room temperature into a firm template, simulating the extent of reconstruction already

patient in supine position (Fig. 10). Casting the implant, particular attention has to be drawn to the desired contour and especially to the edges of the mold to achieve a pleasant result of the corrected deformity without any undesired protrusion or rolling-up of its margins. Marks in 1984 [7] noticed that skin and subcutis thickness above the sternum differs from the thickness at the parasternal area, where it becomes thicker. This anatomical attribute also must be taken into account during subtle sizing the mold in order to prevent unpleasant contour deformity with an unnatural appearance after implantation of the final fabricate. It is also important to recognize that the skeletal defect may even be smaller than the external apparent defect, especially in well-trained athletic male patients (Figs. 7 and 8) or females with well developed or hyperplasic breasts. It is generally preferable to slightly undersize the mold in order to avoid protrusion and reconcilability of the whole implant or parts of it. Based on this mold and selecting the appropriate quality of softness or pliability a silicone implant will be fabricated (Figs. 9 and 12). In most of the cases the quality "soft" besides three others represents the ideal quality to fill up an uncomplicated excavation. Especially in slim patients or when the implant is subject of insertion via a remote skin incision, the quality "extra soft" might be advantageous for the passage through a long tissue channel.

Upon receipt of the final product from the manufacturer, noteworthy that the production processing may take several weeks, surgery will be scheduled.

6.5.3 Surgical technique

Surgery is performed with the patient under general or local anesthesia, the latter may be feasible in smaller defects only. In male patients, the skin incision (4–8 cm) is made horizontally in the direction of skin tension lines [10–12] for less visible scarring (Chapter 5.1), the length depending on the size and pliability of the implant (Figs. 10 and 11).

In female patients, an incision is preferably made along the medial part of the inframammary crease. A subcutaneous pocket is then prepared above the sternal periosteum and pectoralis major muscle fascia. Because of the elasticity/pliability of the silicone implant, a short skin incision sufficiently serves for insertion of a folded implant into the pocket (Fig. 12). For efficient blood coagulation in the subcutaneous pocket, a Langenbeck hook equipped with a light source likewise to an illuminated Biggs retractor [13] is used (Fig. 13). Afterward the silicon implant is inserted into the pocket and suction drains are left in place usually for at least 3–7 days, depending on the size of the pocket and extent of fluid production. To prevent postoperative hematoma, a compressive dressing with foam material is applied for 2–4 weeks. Dislocation of the implant during the postoperative period usually is no concern as long as the pocket matches the implant in size perfectly. That is why particular attention has to be drawn to proper dissection of the subcutaneous plane, exactly outflanking the borders of the implant and its designated

Fig. 10. Intraoperative situs of an athletic patient with an asymmetric pectus excavatum deformity. Notice the skin incision along the RSTL, the very pliable but large-sized implant and two drains already placed with a remote exit through the skin in order to reduce the risk of infection

Fig. 11. Skin incision camouflaged by setting it along the RSTL and into the hairy pectoral area

place. Otherwise dislocation especially along the gravitational forces to caudal or malrotation will become a cumbersome complication.

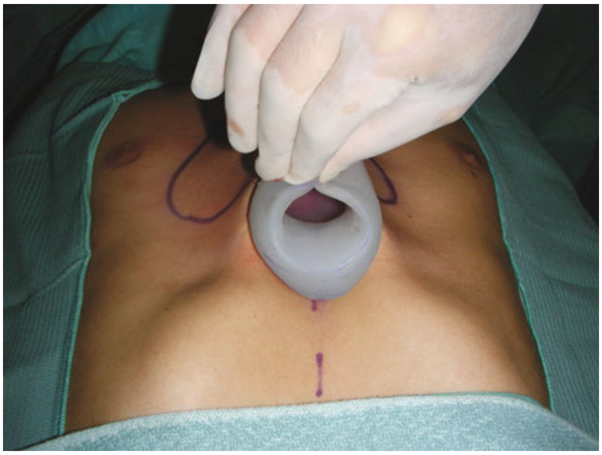

Fig. 12. Folding of the smooth silicone implant in order to keep the skin incision small

Fig. 13. A Langenbeck hook specially designed with a fixed plug to hook a cold light source in order to directly visualize structures deep within a tissue pocket

While some surgeons propagate a so-called "overriding" of the pectus excavatum deformity by implantation of breast implants, which usually are designed for breast augmentation, this procedure is succeeding only under special circumstances. If for example an asymptomatic and only minor and particularly symmetric depression of the thoracic wall exists, with hypoplastic breasts, an exclusive breast augmentation can conceal the funnel breast deformity with implants sufficiently (Chapter 9).

As an alternative, Rose and Lavey in 1982 reported a simultaneous correction of bilateral breast hypoplasia and pectus excavatum using a single-unit prosthesis, consisting of two gel-filled breast implants firmly attached to a central silicone rubber implant [5, 6]. The main advantage of this attachment seems to be that no abrasion between otherwise loosely inserted implants takes place, which reduces the problem of seroma or even scar formation around abraded particles, based on potential foreign body reactions (Chapter 12.3). This abrasive process between a solid silicone block and onlay breast implants, should they have not been implanted in separate tissue pockets or should they have perforated through their own pocket subcutaneously into a conjoined pocket, is accounted for early leakage or rupture of the breast implants. As a modification Marks [7, 13] advocates the placing of the funnel implant deep to the muscles and muscle fascia. The particular advantage herein consists not only in the smoothening of the otherwise occasionally visible transition zone between implant and surrounding tissue, but also in a separation of breast implants from a funnel chest implant by strongly structured muscular and fascial tissue. However, in the presternal region this means pectoralis muscle flaps elevation and transposition to the midline.

6.5.4 Complications

Possible complications with silicone implants generally are result from heavy weight, too hard or too smooth consistency of the implant, formation of a fibrous capsule with ensuing contraction, formation of seroma, downward-slippage due to gravitation and visibility of the implant as a whole or at the edges due to rolling-up, rocking, prosthetic extrusion, late bleeding, and infection [4, 7, 8, 13, 14]. Loss of an aimed natural contour may be a result of overcorrection by using a too large implant, inadvertently again staining the patient. Especially the xiphoid region features a three-dimensional region that might be obliterated by imperfect shaping of the mold. Thus the natural angle of the costal cartilages with the xiphoid should be maintained as an aesthetically important area [13]. For the case that maintenance is not possible because of the nature of the depression, it should be reconstructed with the implant itself.

The high incidence of reported [7–9, 13] hematomas perioperatively is associated with the small access for implantation of silicone blocks in general. Short skin incisions are desired to minimize the length and reconcilability of a scar, the nowadays available silicone implants show sufficient pliability to pass through very small incisions. On the other hand such a minimal access does not allow optimal hemostasis during dissection of the subcutaneous pocket. Such wide ranging subcutaneous dissection for a widespread and flat implant also endangers the blood circulation of the elevated skin, the center of this “tent-roof” might develop necrosis if dissected too close to the skin surface, predominantly in slender patients. Anyhow, the implantation of such foreign materials in slim patients is a problematic endeavor, since almost every implant will be visible and appear in outlines through the thin skin, known as “implant show”. Therefore such an artificially created stain, that replaces the congenital depression indeed, will hardly satisfy the desires and requirements of an afflicted patient. Such a problem of implant show is predominately present in slim patients, but slender young adolescents and adults usually lack of transplantable fat too. Herein also the new advent of lipofilling will hardly fulfill the requirements of tissue augmentation in the presternal area (Chapter 6.6.2). Snel in 2009 [9] advocated the lipofilling procedure (autologous fat from abdomen, buttocks, thighs) several months prior to silicone implantation in order to enhance the thickness of the subcutaneous layer in the presternal area to avoid later implant show. An appropriate patient therefore must be properly evaluated for suitable fat deposits, sufficient in location and volume for serial lipofilling procedures. Even the microvascular transplantation of tissue flaps (Chapter 6.6.4) in such slender patients will probably not lead to a pleasant result, creating additional scars and show of flap contour beneath a very thin skin layer instead. Not even autologous transplantation cartilage chips, taken from occasional overgrowth of lower ribs (Chapter 6.6.1) might be helpful in such cases, because the agglomeration of these cartilage fragments will be easily palpable and worse, will be visible through the flimsy skin. In these cases it might be a wise solution to accurately inform and convince the patient to await maturation of the body for several years prior to perform surgery with an expectable unsatisfying result. In the meanwhile Macrolane™, a biological substance consisting of hyaluronic acid, may serve for temporary augmentation of the depressed area. Though very expensive so far, multiply applied as a filler for facial wrinkles, this substance nowadays is utilized in breast augmentation too [15]. Yet without evidence-based studies and without available literature for the application in the funnel chest deformity the augmentation effect of this substance is reported to last up to 18 months in facial rejuvenation [16]. Due to resorption, which is an effect of natural degradation of its polysaccharide components, the augmentation or filling effect will vanish by time, thus the procedure must be repeated until body maturation will provide with sufficient transplantable subcutaneous fat tissue.

Besides hematoma formation seroma production predominately is the main concern in the utilization of silicone implants for reconstruction of the pectus excavatum depression. In patients in whom seroma occur, this effect may be caused by foreign body reaction to a widespread silicone surface (Chapter 12.3). This happening is quite unpleasant for the patient because serial aspiration is required in order to reduce pain and prevent over-distension of the skin with ensuing probability of remaining skin wrinkles, furthermore with every aspiration the danger of iatrogenic infection increases. However, aspiration of seroma is a requirement in order to avoid distortion or even dislocation of an implant floating within the seroma deposit.

Several authors [8, 9, 17] described 31–65% of patients developing seroma with the repeated need for aspiration due to undue skin bulging and pain. This phenomenon was described also by other authors [4, 7, 14]. However, in the earlier cases the utilization of different kinds of polymerized silicone was accused to that complication, but also nowadays, with the utilization of prefabricated and smooth textured implants this problem is still present. Thus informed consent must include this still very frequent complication. Even 20% of the collective treated in this series developed hematoma requiring secondary surgery for evacuation. The main cause for the high incidence of hematoma may be based on the transection of many intercostal and parasternal musculocutaneous perforating vessels, which immediately retract into the musculature and therefore are hardly accessible for proper hemostasis through a desirably small skin incision, the more, if this incision is placed remote from the implantation site for aesthetical reasons. Therefore the above-mentioned Langenbeck light-hook (Fig. 13) with the spotlight reaching into the deepest recesses is strongly recommended for the survey of a meticulous dissection and hemostasis. As an additional step against seroma or hematoma formation the application of an elastic, circumferential dressing, with steel- or cotton-wool serves with slight compression at the area of the implant. The compression must be adapted to the situation, that the elevated skin flaps, due to transection of many musculocutaneous perfora-

Fig. 14. Implant with a textured surface. This kind of superficial structure apart from material tongues or incisions also is suitable to prevent dislocation and should enable firm attachment to the surrounding tissue.

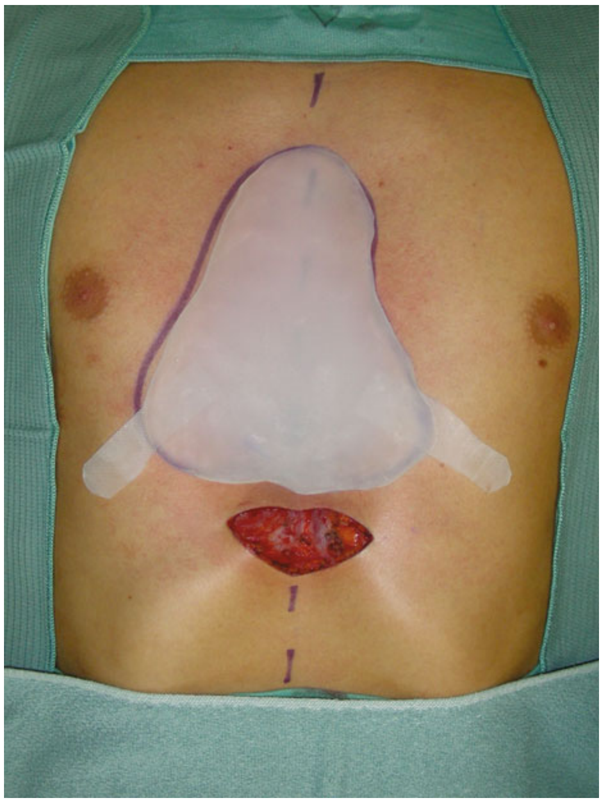

Fig. 15. A large smooth silicone implant equipped with silicone straps, designed for additional subcutaneous fixation to prevent rotation

tor vessels possess lesser perfusion, thus the development of skin necrosis can be a result of too tight dressing.

According to the report of Marks in 2000 [13], but currently still with lacking evidence due to the available small cohorts of patients, seroma formation is decreased when the implant is fabricated with a textured surface (Fig. 14). This texture additionally allows tissue ingrowths into the rough superficial structure thus provides with firm adherence and subsequently decreases the risk of displacement or rotation as well as seroma formation. Another possibility to prevent rotation is the fabrication of silicone straps fixed to it. Those straps may be adhered to fascial structures with non-absorbable sutures (Fig. 15).

Asymmetric deformities of the anterior thoracic wall with tissue depression, not diagnosed as funnel chest, but summarized as miscellaneous deformities (Chapter 2.3), appearing as a single deformity or conjoined with other deformities may also be subject of treatment with silicone implants [18]. Particularly lateral depressions of rib cartilages and bones are hardly accessible for any type of surgery, as well as depressions at the lower thoracic wall involving the seventh to tenth rib. Besides congenital deformities, asymmetric flattened or even caved deformities may also be an iatrogenic result of remodeling an asymmetric funnel chest. Even in the keel chest deformity such excavations may be present and cannot be resolved by conventional rib and cartilage remodeling. For such cases autologous tissue augmentation like lipofilling (Chapter 6.6.2) or cartilage chips (Chapter 6.6.1) may serve for permanent improvement, but also custom-made silicone is ideally suitable for these minor, due to predominately asymmetric appearance and thus aesthetically unpleasant defects (Figs. 16a, b and 17a–c).

Molding and prefabrication does not differ from the technique described above. Placing of the incision along the RSTL (relaxing skin tension lines) may be remote from the midline or the defect itself in a hidden area. Usually such depressions present shallow but widespread, so that a prefabricated silicone implant may easily be folded or rolled for insertion through a minimal skin incision. The reluctance against such a small port for implant insertion is the limited survey during pocket dissection. This problem may be overcome either by using an illuminated skin retractor (Fig. 13) or an endoscope for the case of a very distant skin incision [19, 20].

Overall, the silicone implant in the hands of experienced surgeons shows contentedness from 69% up to 95% of the patients treated even in the long-term evaluation [8, 9]. Thus and because major surgery can be avoided, this alternative can serve as a first choice of treatment in selected cases for aesthetic

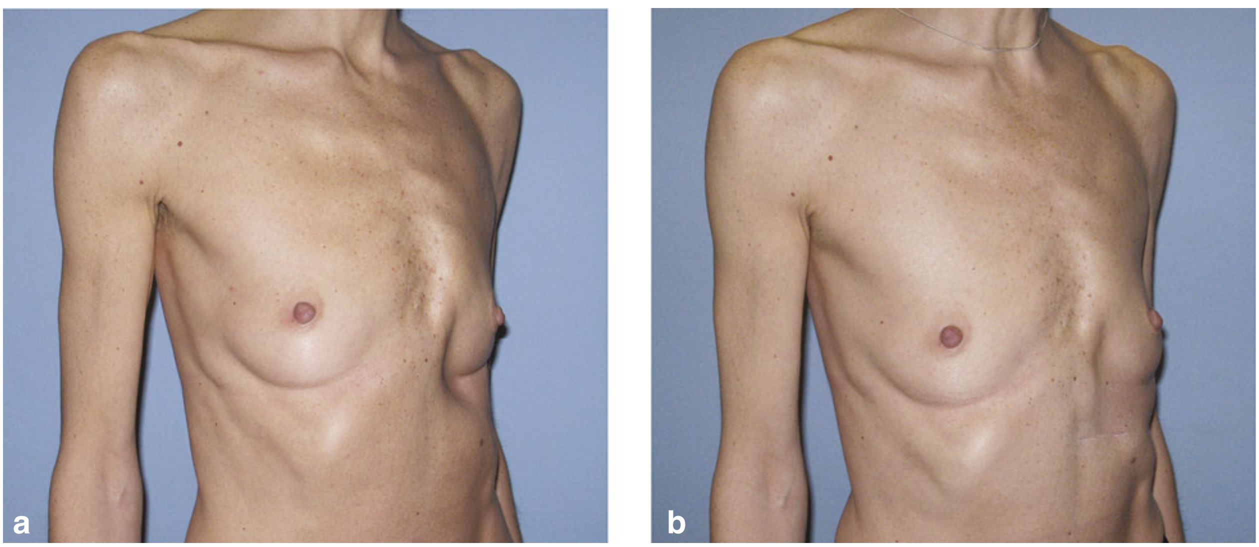

Fig. 16a. A 45-year-old extremely slim female with asymmetric depression at the left lower thoracic region, distortion of the left breast to caudal and inaccessible for distinct thoracic remodeling surgery. **b** Same patient 14 months after implantation of a flat and soft custom-made silicone “leaf” with stable and aesthetically very satisfying result. Even the breast on the left side improved its projection now almost symmetrical to the contralateral unaffected side

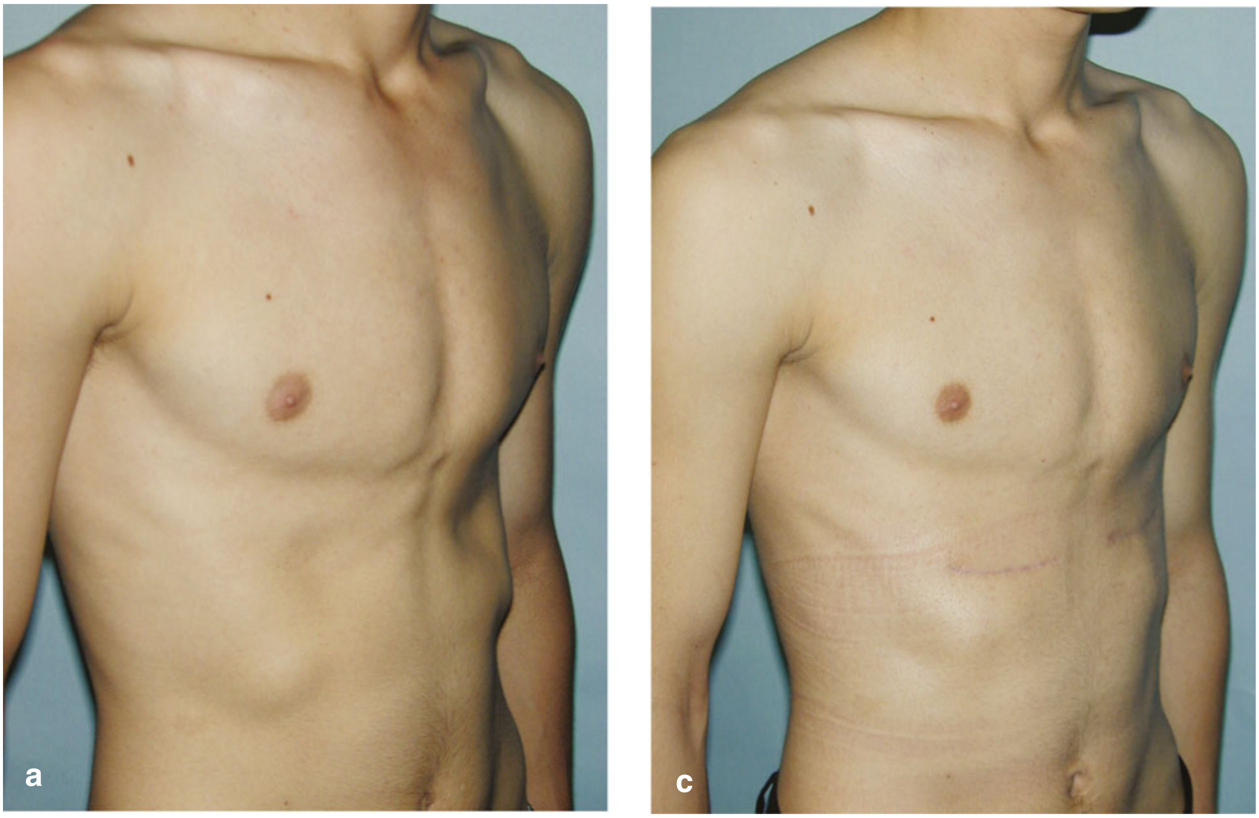

Fig. 17a. A 18 years old male preoperatively with major depression of the ribs at the left infrapectoral region and minor at the right side. **b** Custom-made silicone implant with the quality "XS" (extra soft) upon receipt by manufacturer and prior to sterilization. **c** Same patient 6 months after subcutaneous silicone augmentation

improvement of the pectus excavatum deformity, despite the high incidence of minor complications. Silicone implantation is ideal in adults, when the body has reached its final skeletal shape and contour and cardiopulmonal impairment is absent. Nevertheless many patients refuse the use of foreign body, but alternatives with transplantation of autologous tissue in many cases can afford relief of such circumstances, however, creating donor defects and additional scarring. Informed consent must contain all the advantages and disadvantages of silicone and alternative procedures as well [9].

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6.6 Autologous tissue

6.6.1 Cartilage chips for treatment or refinement in funnel chest deformity

Anton H. Schwabegger

The application of autologous cartilage is well established exemplarily for nose reconstructions or other regions at the face already since many years [1–7, 9]. Such autologous cartilage grafts, herewith harvested from deformed ribs preset themselves also very well suitable to fill up minor or minimal funnel chest deformities. In contrast to alloplastic material, such as silicone or artificial bone, autologous grafts serve as volume replacement lifelong, as far as they grow in without resorption. They exemplarily can be used for the adjustment of asymmetrical contours and small remaining irregularities, which still annoy the patients after corrections of a funnel depression using a pectus-bar or applying other techniques. Sometimes and not before several months after the elevation of an asymmetrically one-sided distinct deformity, an undesirable gibbus at the contralateral side then may result as a minor but well-recognizable hump. This gibbus, it usually concerns only single rib cartilages directly at the junction zone to the sternum, can be resected out or cut tangentially within the same surgery as the bar explantation, however using separate incisions presternally or parasternally. These cartilage parts as a by-product may then be used to fill up remaining small-depressed areas of the anterior thoracic wall, which were not manageable by the initial surgery. In contrast to the application in nose augmentation, the rib grafts are thoroughly cut to small chips of not more than 5 mm in diameter by scalpel, wrapped into bioabsorbable hemostyptic and antimicrobial fabric (Tabotamp™ or Surgicel™ by Johnson & Johnson Corp., New Brunswick, NJ, USA) and then placed into a subcutaneous pocket encompassing the concerning depression (Fig. 1a–g).

If such an asymmetrical contour with unilateral depression and projection of a gibbus should become apparent immediately during implantation of a pectus-bar with a semi-open access, when cartilage rib parts devolve from necessary chondrotomies, the resulting contour deformity may be adjusted to a symmetrical surface immediately utilizing these cartilage chips (Fig. 2a–c).

In minor but distinct forms of the pectus arcuatum deformity such cartilage chips-transplantations outstandingly suit for correction, if for example osteotomies or a pectus-bar implantation meant surgical over-treatment and solely the necessity consists to cut off excess of those cartilages which cause the gibbus (Fig. 1a–e, Chapter 8).

The cartilage pieces to be resected are either taken subperichondrially or otherwise meticulously freed from perichondrium. The cleansing of that perichondrium is mandatory, because reimplanted perichondrium could, above all at the youth, which are subject of skeletal growing, produce undesirable contour irregularity through cartilage neogenesis and therewith even might deteriorate the intended aesthetic improvement and final result.

The cartilage chips become minced to small pieces of not more than 5 mm in diameter (Fig. 1a) using a Lür, a Liston or preferably scalpel. On the one hand this diminishing of the cartilage grafts to small chips has the advantage that this cartilage gravel can easily be contoured after the implantation into the subcutaneous tissue pocket (Fig. 1f). So that however this cartilage gravel does not arrive at undesirable localizations, it is enveloped with rapidly bioabsorbable cellulose fabric layers for example, is moistened with saline (Fig. 1c) thus temporarily fixed in a desired shape [4, 8]. In addition or instead of this cellulose fabric, also Spongostan™ (Johnson & Johnson Corp., New Brunswick, NJ, USA) or fibrin glue (Tisseel™, Baxter International Inc., Deerfield, IL, USA) can be used [3, 8]. Ideal shaping of the cartilage gravel though is dependent on an exactly dissected tissue pocket, and for the case of embedding with fibrin glue, after its hardening that occurs within seconds, adaptive shaping is hardly possible any more. That means that prior to the injection of fibrin glue the shaping or modeling of the cartilage gravel must be terminated already.

On the other hand, mincing of the cartilages augments their surface to establish sufficient contact with surrounding vascularized tissue, which enables ingrowth and prevents necrotization with ensuing resorption.

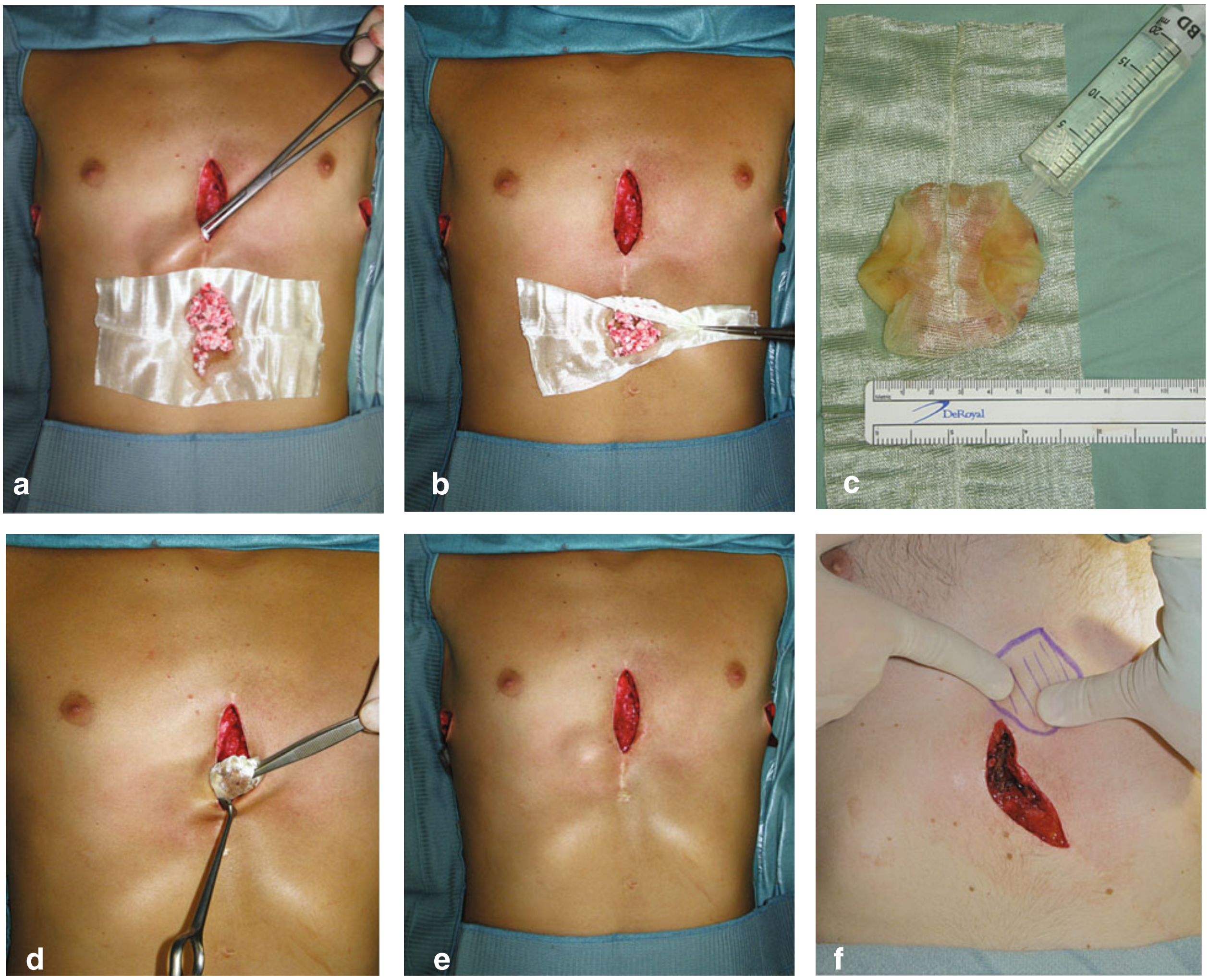

Fig. 1a. A 16-year-old boy with pectus excavatum, corrected by MIRPE and minimal anterior access for supportive sternum elevation through an old presternal scar. Simultaneous augmentation of a right-sided depression (forceps) with autologous cartilage chips already cut and placed on a Surgicel-sheet. **b** Wrapping of the cartilage grafts with Surgicel. **c** Moistening of Surgicel for smooth package of the cartilage grafts. **d** Implantation of packed grafts into the dissected subcutaneous pocket. **e** Implanted graft mass, yet causing exceeding hump, prior to molding. **f** Manual molding of subcutaneously (marked area) implanted grafts to obtain a plain and inconspicuous skin surface, demonstrated in another 21-year-old patient with simultaneous correction of an old scar, resulting from diaphragm surgery in childhood. **g** Final situation after molding (patient of e) and prior to wound closure

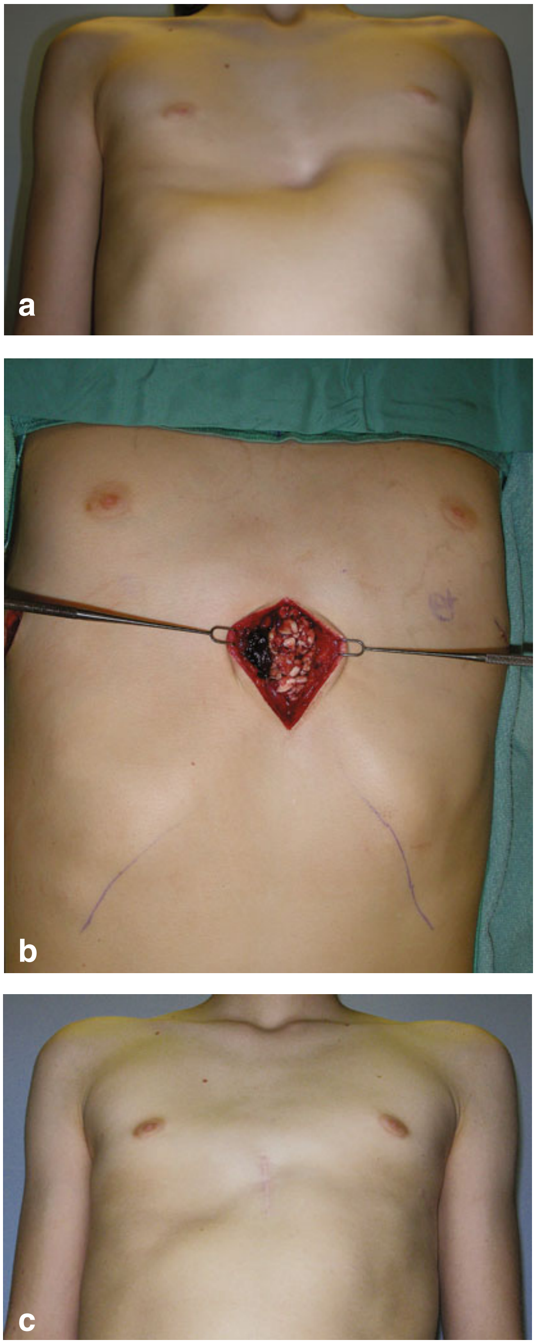

Fig. 2a. A 16-year-old male with asymmetric pectus excavatum, prior to MIRPE and minimal central access. **b** The MIRPE procedure caused gibbus formation at the left side, the resulting hump was simultaneously resected and the by-product cartilages were implanted as chips to egalize the remaining irregular depression for aesthetic improvement of the skin surface. **c** Situation 1 year after pectus-bar explantation, 2 years after initial surgery and simultaneous cartilage grafting

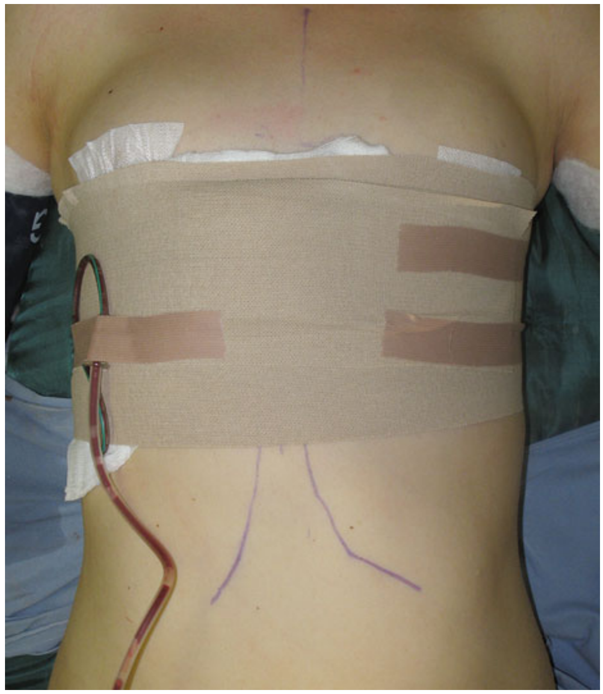

Fig. 3. Elastic bandage for moderate compression of transplanted autologous cartilage chips to avoid dislocation and to enable close contact of vascularized tissue for rapid ingrowth thus minor resorption

In contrast to foreign material like silicone implants (Chapter 6.5) autologous cartilage on a long-term basis is more durable and also more economical. However, the maximal layer thickness of the cartilage gravel should not exceed 1 cm so that a complete ingrowth of the cartilage chips with connective tissue and scar is enabled and therefore disintegration of transplanted tissue by resorption processes caused by lesser or lacking perfusion can be avoided. This maximal layer thickness of 1 cm therefore means the (personally experienced, no valid data available so far) limiting factor for the filling-up of a funnel chest depression in one stage. Partial resorption can be disadvantageous, which under circumstances may produce contour irregularity of the engrafted mass. This unpredictable irregular resorption rate still means a major issue in cartilage grafting, published in series of reconstruction or augmentation rhinoplasty [1]. However, such irregularities at the nose will much more bother a patient due to aesthetic thus psychological reasons, but will not at that extent in the patient with pectus deformities. That is because the presternal and surrounding skin presents much more rigidity than the skin at the nose and therefore

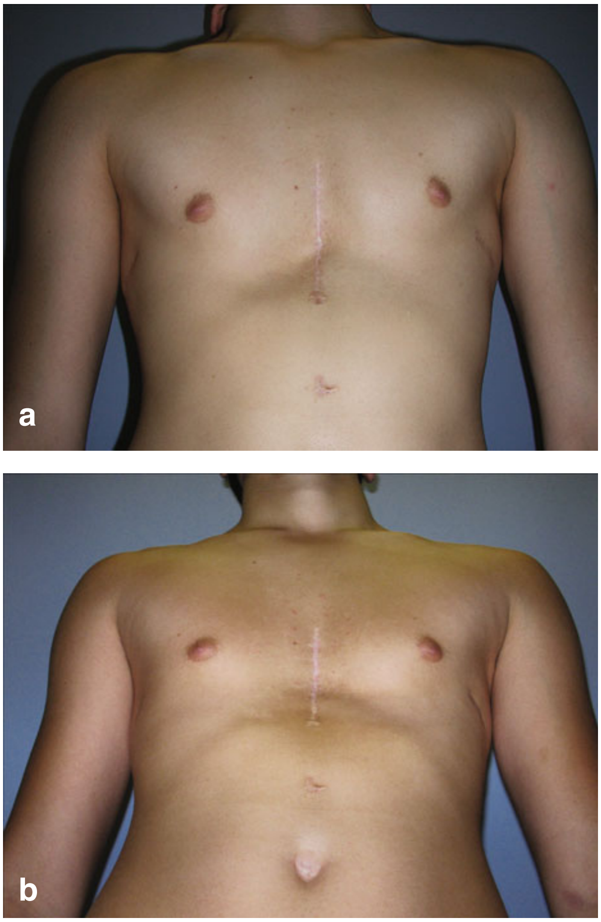

Fig. 4a. A 17-year-old boy, situation 1 year after pectus-bar implantation according to the Nuss procedure, combined with minor open presternal access, prior to pectus-bar explantation. Notice remaining asymmetrical depression at the left paraxiphoid area. **b** Same patient 11 months after pectus-bar explantation and simultaneous depression augmentation with cartilage chips, resulting in pleasant contour symmetry

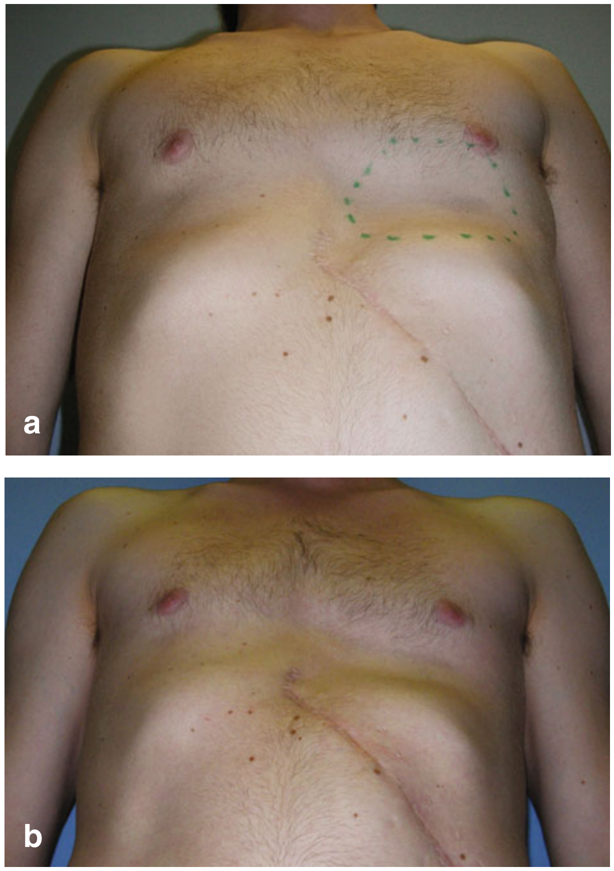

Fig. 5a. Same patient as in Fig. 1f, situation 3 years after MIRPE with one bar, prior to its explantation, notice circumscribed (marked) rib depression at the left side. **b** Situation 1 year after pectus-bar explantation and sufficient improvement of the left-sided depression by simultaneous augmentation with autologous cartilage chips

irregularities are much better concealed by that quality. Furthermore, slight surface irregularities resulting from partial resorption of grafts in most of the cases still cause contentedness of the patients because of mostly sufficient augmentation of any cavity. If augmentation of a deeper depression solely with cartilage chips is aimed, it should be scheduled and performed in two or more stages, separated by intervals of at least 3 months. The encompassing area of tissue augmentation on the other hand is limited through the quantity of available cartilage that can be harvested without resulting problems at the donor site. Until the fixation of the transplanted cartilage gravel by endogenous embedding scars, a rib bandage (cingulum) with moderate compression onto the modeled region should be carried for 4 weeks (Fig. 3).

Above all in the secondary corrections with aesthetic refinements, the cartilages available by necessary resections usually suit outstandingly for contour adjustments of smaller asymmetric sunken defects caused by any prior remodeling procedure (Figs. 1a and 4a, b). On the other hand, especially in very slim patients, the contours of cartilage grafts placed subcutaneously may be visible and easily palpable. Furthermore in the primary intervention of only small or moderate defects, when no surplus of cartilage is available, the removal of cartilage out of "healthy" regions is not indicated or not desired. Therefore further methods are described in Chapter 6.6.2; exemplarily the nowadays re-developed and refined technique of lipofilling substantially appears more suitable in distinct cases because of its simplicity and lesser invasiveness, however, as long as sufficient subcutaneous fat is available for liposuction.

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6.6.2 Lipofilling for funnel chest and similar or adjacent anterior thoracic wall deformities

Monika Mattesich, Anton H. Schwabegger

6.6.2.1 Introduction

The transfer of autologous fat as whole grafts has been performed since the end of the 19th century and as injectable grafts since the 1920s; however, it is only within the past 20 years that the popularity of autologous fat transfer for the correction of various deformities has increased within the plastic surgery community. The rising interest in this procedure has paralleled the development of liposuction for body contouring. One reason may be the natural tendency to capitalize on the opportunity that the removed fat may be used to augment or restore areas at the body or face [17] with volume loss, contour irregularities or congenital deformities. Plastic surgeons most experienced with fat filling procedures have reported good clinical results suggesting short- and long-term persistence of transferred grafts, and thus promote autologous fat as the ideal filler [8, 10, 13, 22].

Despite the initial clinical optimism associated with autologous fat transfer, there remains an uncertainty among physicians regarding the viability of transferred fat [2]. A critical assessment of the literature seems to object to the consistent success of the procedure. Animal studies by Peer [18] have failed to demonstrate the longevity of transplanted fat. Furthermore, only few clinical reports have applied objective outcome measures that document fat survival. Surprisingly, this has not decreased physician's enthusiasm for this technique. Modifications of the original techniques have been reported by Coleman, who promotes an atraumatic method of fat harvesting, centrifugation, and reinjection with the aim of maximizing nutrition and structural integrity at the recipient site [4]. He reports high physician and patient satisfaction from his "structural fat grafting" technique [9]. The heightened interest in autologous fat transfer by patients and physicians should arouse objective investigation. Advances in three-dimensional surface mapping (see Chapter 9.1) with laser scanners and professional photography (see Chapter 3.1) now allow inexpensive methods for documentation of fat grafting techniques. It is assumed and hoped that future tissue engineering techniques with adult-derived stem cells will admit long-lasting results and more predictable outcomes [16].

6.6.2.2 History

Neuber at the 22nd Convention of the German Society of Surgeons gave the first lecture on autologous fat transplantation to the periorbital region in 1893. It were Lexer, Czerny and Rehn who reported on similar methods in thoracic-, abdominal- and breast-surgery over the following decades. In 1911 Bruning used autologous fat for the correction of subcutaneous defects [1].

Although there was initial optimism expressed in these reports, subsequent studies noted that grafts diminished in size after transplantation. These studies recommended overgrafting to account for the loss in restorative volume by natural resorption. Marchand histologically examined transplanted human fat tissue blocks and observed that a large central portion was nonviable after 10 weeks; however, peripheral sections bordering connective tissue showed proliferation. In his review of the literature in 1923, Neuhof reported that fat undergoes a similar process like transplanted bone, whereby fat dies and is replaced by fibrous tissue or newly formed fat.

In 1950, Peer documented that free fat grafts loose approximately 40% of their weight and mass per year. On the basis of microscopic assessments of harvested grafts, he assumed that durable fat cells were concentrated in the center core of a graft and the remainder of the cells degenerate. In a follow-up report Peer emphasized the importance of both the need of hemostasis to maximize survival of the graft and a good blood supply at the recipient site [19].

These findings were similar to those of other investigators over the subsequent three decades [16]. This corresponded to a declining interest in fat grafting by physicians who were concerned about inconsistent and unpredictable results and therefore the technique was not widely used.

6.6.2.3 Current investigations

In the early 1980s, liposuction turned out to be the most frequently performed procedure of aesthetic surgery and it provided plastic surgeons with a valuable by-product: semi-liquid fat that could be grafted with relative ease using needles or small cannulas [9].
In many ways, fat is the closest that exists to an ideal filler: it is readily available and not expensive; it is autologous and therefore lacks a host immune response; it is safe and noncarcinogenic; and it is easily acquired with a minimal invasive procedure [15].
In the early 1990s, a series of positive reports of fat grafting were published [11]. One of the promoters among them was Sydney Coleman, who postulated that “his experiences with fat grafting have confirmed the efficacy and permanence of grafted fat, provided that it is handled atraumatically and that proper harvesting and grafting technique is followed”. His consistent publications show that fat grafting can result in long-term corrections [3–7]. He began to observe other attributes of fat. He noted that the quality of the skin under which grafted fat was placed improved, not only as an effect of the fullness but also with gradual improvement in the quality of the skin. Wrinkles softened, pore size decreased, and pigmentation improved over the first year. There also appeared to be an improvement in the quality of the tissues into which fat was grafted. In the late 1990s, he reported that fat grafted under depressed scars not only relieved the depression but also seemed to soften or even completely eliminate the visibility of a scar, turning the appearance to look like normal skin, so that the effect of grafted fat seemed to be much more than just a long-term filling [5].

6.6.2.4 Indications

Nowadays, the technique of autologous fat transfer is widely spread. We can find numerous publications on its applications for all kinds of subcutaneous soft-tissue defects, lipoatrophies [17], the treatment of breast capsular contracture [24], chronic skin ulceration [12], the treatment of radiation skin damage [14], of mild pectus excavatum [20] and its application in Poland’s syndrome [23].
In this chapter the emphasis is put on the one hand on the application of autologous fat transfer for the correction of mild chest wall deformities as a primary therapy option. On the other hand, it has shown to be a valuable alternative for the correction of residual defects of chest wall deformities after minimally invasive, open or combined correction techniques (Nuss, Ravitch, etc.) and after correction with custom-made silicone chest wall implants or conventional breast implants, respectively.
It can also be taken into consideration for the aesthetic correction of distinct presternal scarring.

6.6.2.5 Technique

The procedure is usually performed under general anesthesia. Patient’s position is supine; fat is taken from the abdomen or thighs in the conventional wet technique. At our department, we use a special liposuction device (Tissu-Trans® by Shippert Medical Technologies Corporation, USA). Fat is harvested in routine fashion using back and forth motion. It will remain in the specially designed syringe with a multitude of sidewise perforations, and all blood, fluid and waste will be suctioned out to the waist canister (Figs. 1–4).
When the syringe is full or the desired amount of fat has been obtained, the harvest tubing is removed from the outer casing, a sleeve is pushed over the fat-filled syringe and a plunger is inserted into the end of it. A cannula is attached and the harvested fat is now ready to be re-injected into the designated areas.

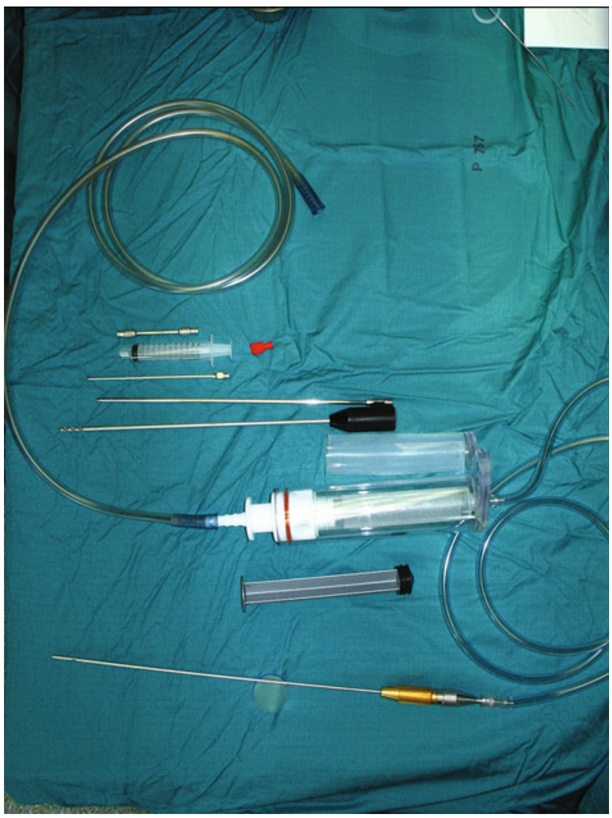

Fig. 1. The Shippert Tissue-Trans™ Model 60 for liposuction and simultaneous reinjection utilizing the same 60 ml syringe

Fig. 2. Technique of liposuction exemplarily at the abdomen to harvest an appropriate amount of fat tissue for transplantation

Fig. 4. Fat transferred to small syringes for a more convenient handling and portioning during injection

Fig. 3. Occasional fat separation from dispensable fluid and transfer to small syringes

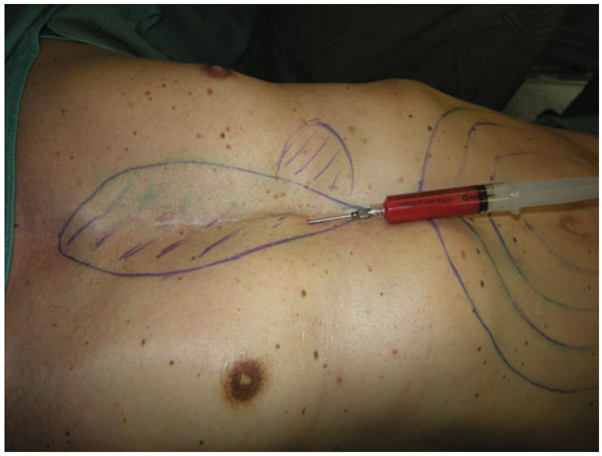

Fig. 5. Technique of injection of fat tissue in chains, multiple layers and fan-shaped, in order to prevent resorption

After successful suctioning, local anesthesia with adrenalin as a vasoconstrictor is injected into the donor site to avoid hematoma.

6.6.2.6 Graft placement

Fat grafts are placed into the subcutaneous layer. Injection is undertaken via a fine cannula with multiple passes, injecting only tiny amounts with each pass and with deposition of fat in chains as the cannula is withdrawn. Ideally, fat is deposited at varying levels in a fan-shaped and atraumatical manner as this increases the surface area for contact with nourishing capillaries, as well as providing a more desirable aesthetic result (Fig. 5).

6.6.2.7 Discussion

Although there is a current trend in replacement and recontouring of almost all kinds of subcutaneous tissue deficits with autologous fat transplantation [25], the literature fails to provide definitive evidence of survival of the transplanted fat [26]. Modern molecular biology techniques such as cell-labeling and the ability to monitor cell trafficking will provide more answers to clinicians' questions. In addition, a large-scale clinical assessment using three-dimensional volumetric imaging would supply useful data (see Chapter 9.2).
Nevertheless, several but so far preliminary results indicate that lipofilling can improve aesthetic results after correction of various chest wall deformities in-

cluding the female breast. It is speculated that this improvement depends on tissue regeneration promoted by adipose tissue-derived stem cells. However, further research must be undertaken to assess these adipose cell properties, extra-cellular matrix composition, and the essential requisites for routine clinical applications should be investigated prior to a routine application.

The morbidity related to lipofilling is rather minimal, similar to that for a limited liposuction, with acceptable safety. It is a reliable and reproducible technique with negligible residual scarring and few complications (such as fat necrosis). In order to reduce the risk of fat necrosis, a strict injection technique should be adhered to and excessive injection of fat should be avoided. It is virtually impossible to define an ideal volume that should be transplanted, because this depends on various factors such as patient's morphology, the amount of fat available, the quality of the skin and the volumes and location treated. Injection of a maximum amount of 200 cc per session is recommended, as long as the technique of fan-shaped injections into different layers is feasible.

Promising results documented for other applications of lipofilling give hope for equally positive outcomes of its application in minor chest wall deformities, for the adjustment of asymmetrical contours and remaining small irregularities that might still annoy patients after various corrections as the implantation of a pectus-bar or other techniques (Figs. 6, 7).

Fig. 6. A 46-year-old man with recurrent funnel chest deformity after several operations elsewhere (Rehbein approach in childhood, Ravitch and pectus-bar technique as an adult). For a further aesthetic improvement and treatment of the adherent presternal scar one session of lipofilling with 100 cc was performed

Fig. 7. Preliminary result 2 weeks after lipofilling for release of the presternal scar and minor tissue augmentation. A second and possibly third session of lipofilling may continue the aesthetic improvement

An autologous fat tissue graft, mostly used as a complementary treatment, improves trophicity if the integument is thin, gives better definition to the reconstructed contours and adds bulk in completion of the

Fig. 8. A 42-year-old woman with persistent asymmetric pectus arcuatum deformity after several operations with breast implants on both sides and sequential presternal custom-made silicon elastomer implants. Lipofilling with 55 cc to the left breast and to the presternal region. Simultaneous correction of the ipsilateral submammary fold and of a remaining bulk of the second rib cartilage on the right side

Fig. 9. Preliminary result 6 weeks after lipofilling. Minor improvement at the funnel deformity itself but notably better contouring at the inner and upper margin of the left breast implant. The remaining funnel would need further lipofilling

conventional techniques. However, several injection sessions are necessary due to the unpredictable amount of resorption of the transplanted tissue, but can often be associated with other corrective or refinement procedures.

Lipofilling enables improvement of the quality of the results, which often seem to be imperfect if only a single approach or operation technique is performed.

In the future autologous fat injection for minor chest deformities may be considered as an alternative to other more invasive procedures. Lipofilling might replace the implantation of small custom-made silicone elastomer implants and can even be applied for larger presternal depressions. It is also applicable for the correction of breast asymmetries associated with the thoracic wall deformity (Figs. 8, 9), since the radiographic appearance after injection does not seem to lead to confusion with malignancy and does not interfere with such diagnostics so far [21].

It should be kept in mind that the discomfort of minor chest wall deformities is almost always aesthetic and that in most cases it has no functional impact. Surgeons must therefore propose the most appropriate treatment for each patient, causing of course the least morbidity, leaving minimal scarring and functional sequelae, which may be credited as an argument for autologous fat transplantation by the lipofilling technique in minor and moderately sized deformities or as an adjunct to refine major corrections.

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6.6.3 Local flaps

Anton H. Schwabegger

If invasive methods of thoracoplasty like sternum turn-over, costochondrosternal remodeling or less invasive MIRPE surgery are refused by the patient or contraindicated due to normal fitness and/or only minor expression of the pectus excavatum deformity, local or distant transposition of autologous tissue, may be an alternative treatment option. However, generally in children and adolescents as well as in adult males never sufficient tissue volume is available in the parasternal region for the purpose of filling up a funnel depression through simple tissue transposition. Distant flaps like the TRAM-flap [9] or an omentum-flap [3] exemplarily can be transposed into a central funnel chest defect indeed, in analogy to defect cover for example in osteomyelitis of the sternum or after tumor resection [2, 15]. Even a vascularized rib strut [7] may aid in remodeling, but therein is used as a living support for the elevated sternum, that is mobilized according to the standard Ravitch procedure. Thus such a vascularized rib strut will not directly contribute to volume augmentation, but rather will maintain the position of an elevated sternum.

In predominantly aesthetic indications and young patients, such invasive interventions interfering with the body static or with opening of the abdominal cavity are considered rather contraindicated, however, as long as simpler and less invasive methods are available. Alternatively a pedicled latissimus dorsi muscle (LDM)-flap may be transposed [14], but with the disadvantage of loosing the posterior axillary fold and muscle function to some extent [1]. Moreover to reach the funnel cavity sufficiently just by transposition, the LDM must be detached from the humerus and furthermore its (thoracodorsal) nerve must be transected to avoid inadvertent muscle contractions at the anterior thoracic wall. This denervation will cause atrophy of the muscle, which especially in slim male patients will result in reasonable loss of volume within the augmented space thus will lead to minor aesthetic outcome, if not overcorrected by inclusion of fibroadipose tissue in advance [14]. On the other hand, if transposed in youth and slenderness, transposed fibroadipose tissue adjacent to the LDM may become bulky with increasing body mass during maturation, thus resulting in an unpredictable tissue hump localized widespread above the sternum and parasternal area.

Free flap transfer as a further alternative may be a pains taking endeavor concerning microsurgery, if one is not experienced or routinely dealing with such procedures, but nevertheless can be very helpful in large-scaled pectus excavatum deformities (Chapter 6.6.4).

In adult women on the other hand, with eventually hyperplastic breasts or breasts grown asymmetrically (Fig. 1), the surplus tissue of one or both breasts can be used in place of a custom-made silicone implant (Fig. 2) in order to fill the presternal cavity. In analogy to a reduction mammoplasty according to the method after Morestin in 1907 [6] and Piza [8] a discoid-shaped part of breast tissue is dissected (Fig. 3) out of the concerned breast. Only singular reports are available in the current literature concerning the utilization of such regional tissue for the correction of a funnel deformity. Guimaraes in 2001 described the utilization of adipose tissue flaps [4],

Fig. 1. A 24-year-old female patient with moderate but asymptomatic funnel chest deformity and asymmetric breast hypertrophy

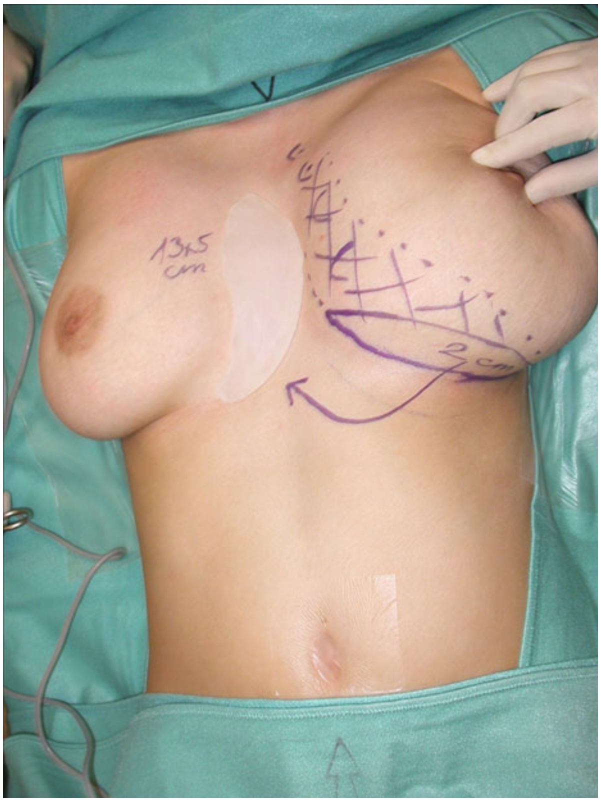

Fig. 2. Intraoperative situs with custom-made (white, semi-transparent, C-shaped) silicone implant already placed on the skin, into the funnel defect. Instead of the silicone implant however, a pedicled flap from the left breast was planned to fill the funnel deformity subcutaneously. The volume of this pedicled breast reduction flap was more than enough to fill up the depression adequately

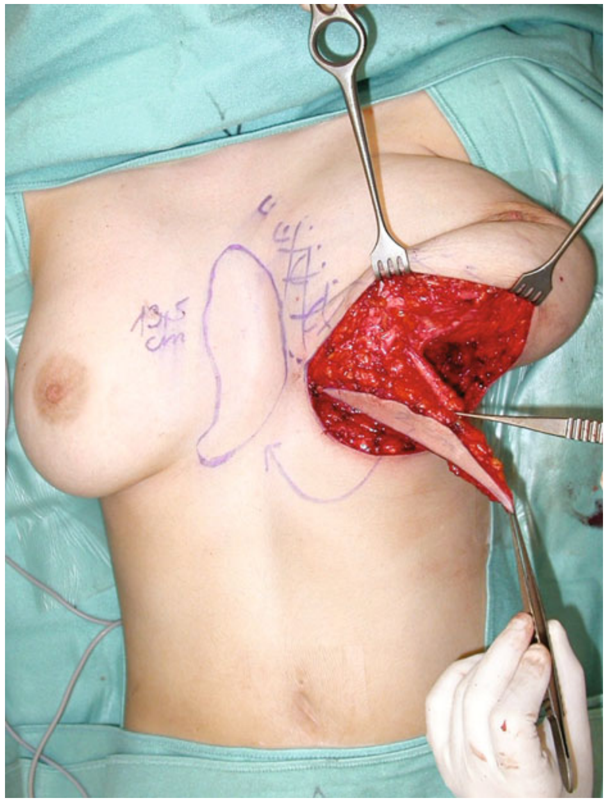

Fig. 3. The pedicled adipo-dermal flap is based on parasternal perforator vessels (indicated by tip of forceps), then de-epithelialized and transposed into a subcutaneous pocket at the presternal funnel. Further surplus tissue of the hyperplastic breast was resected as a discoid from the breast base, resulting in an inconspicuous single scar at the inframammary crease

otherwise surplus tissue and subject of resection during the correction of hypertrophic and ptotic breasts. In this case report such randomly vascularized flaps, based at the lower quadrants of the breasts, were subcutaneously transposed to medial to fill up the pectus excavatum deformity without setting any additional scars. Marshall in 1981 [5] already transposed contralateral breast tissue in oncologic patients, but did this as a two-stage procedure and using a broad medial tissue pedicle. Schoeller in 2001 [11] tried to transpose a contralateral split breast flap for the purpose of breast reconstruction. The relatively large volume flap was based on the perforators of the internal thoracic vessels, but the distal third of the flap had to be discarded due to venous congestion. The pitfall therein seemed to consist in too much tissue bulk that was transposed immediately and based on these perforators, but the anatomical background of that concept gave background to further investigations. Vesely in 2007 [12] and Schmidt in 2010 [10] provided with detailed anatomical studies concerning the internal mammary artery perforators (IMAP) are available, describing its potential use also in central and contralateral chest or breast reconstruction.

In our case described herein, a disk-shaped tissue flap remains vascularized by minor pedicles at the lower medial quadrant and at the basis of the breast tissue cone. This flap is dissected out beginning from lateral and caudal and off the pectoralis major muscle as well as the breast parenchyma. Designed as an island-flap it remains yet nourished (Fig. 3) by several parasternal intercostal perforators medially arising from the internal mammary vessels [12, 13]. This island-flap is de-epithelialized and then transposed to medial. Under circumstances and if the fibroadipose tissue flap presents as a rather stiff tissue bulk especially in adolescents, it can be brought into the

Fig. 4. Very pleasant situation 8 months thereafter without any visible scar, even in an aspect from beneath

funnel depression even as a turn-over flap. It is transposed into the defect and attached there using the same submammary incision by which the subcutaneous pocket extending the funnel cavity is dissected (Fig. 3). The incision at the inframammary crease along which flap harvesting is undertaken will be closed likewise to a reduction mammoplasty with discoid resection [8]. A perfect symmetry however can hardly be obtained (Fig. 4) even with this elegant technique, but two problems simultaneously are settled or minimized herewith. On the one hand hyperplasia of one or two breasts will be reduced and on the other hand the funnel chest deformity may be corrected within a single surgical intervention. The utilization of autologous tissue for filling up a funnel depression means a particular long lasting advantage in contrast to any foreign alloplastic material. It therewith yields a permanent improvement of shape without potential late sequelae after decades, such as capsular contraction, pocket infection or calsifications in the area of the implant capsule. Moreover the skin incision in the area of the submammary crease is designed to allow access both to tissue resection and to flap transposition. Furthermore postoperatively only this single scar remains but usually is completely covered along the inframammary crease by the natural ptosis of the breast. Because only at the cone basis of the breast tissue fat and minimally glandular tissue is harvested, the ability to breastfeed is preserved in any case. However it might happen on the other hand, that during pregnancy these parts of glandular tissue, which are transposed into the funnel, may swell temporarily and postpartally due to lactogenesis, until breastfeeding is ceased. This technique is recommended only in adults after sufficient maturation of the breasts and well-defined submammary crease. It will not be suitable in firm breasts in youth or adolescents without ptosis, furthermore such interventions into growing tissue may result in an unpredictable outcome concerning both the shape of the breast and the funnel deformity. Preoperative mammography or sonography of the breasts is mandatory as a standard routine procedure to exclude any tumor formation prior to use breast tissue for any reconstructive purpose [10, 11].

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6.6.4 Microvascular flaps

Christoph Papp, Wolfgang Michlits

Increasing evidence indicates that funnel chest deformities cause physiologic impairment and limitations, as well as adverse aesthetic and psychological effects [1, 2]. Several techniques have been described to correct this deformity. In the Ravitch procedure, e.g., the deformed costal cartilages are excised, the sternum elevated, and the lower extremity of the sternum supported by perichondrium reefing sutures. Many modifications followed like temporary implantation of Kirschner wires percutaneously, which then had to be removed approximately 12 months after the initial repair [3]. This technique has been modified during decades by some authors using, e.g., a sternal bar (called Adkins strut) for the fixation of the sternum [1, 2, 4, 5]. Nuss described placement of a large curved bar under the deformed chest wall through percutaneous incisions [6]. The bar is kept in place for a prolonged period of time during which the cartilages get reformed in their new position. These two techniques are mainly utilized in children suffering from symptomatic funnel chest to improve cardiovascular and pulmonary function. Ninkovic et al. propagated the free microvascular sternum turnover flap for the remodeling of the thoracal wall in adolescents and adults [7]. Despite these reconstructions that affect the entire thoracic wall are aimed at functional improvement, with all their advantages and disadvantages, some authors described also good aesthetic results using custom-made silicone implants or autologous tissue placed subcutaneously for the correction of asymptomatic funnel chest [8–11]. The indication for the treatment of funnel chest is mainly aesthetic, because up to 95% of the patients do not substantially suffer from cardiovascular or pulmonary symptoms [12]. We therefore prefer the utilization of autologous tissue to correct an aesthetically impairing deformity. At our department we frequently utilize the free groin-flap, the free transverse rectus abdominis musculocutaneous (TRAM)-flap and the free fasciocutaneous infragluteal (FCI)-flap for several other indications of defect reconstruction [13, 14]. Depending on the patient's requirements we select the most suitable flap for each individual patient. Our experience shows that especially in slim patients it is difficult to gain enough autologous tissue volume, e.g., from the abdominal wall or the groin region for an adequate filling of the funnel depression. In those cases and in agreement with the patients we choose to use autologous tissue harvested from the buttock region since this commonly is the only region in the usually leptosomatic funnel chest patients which provides with adequate tissue bulk.

6.6.4.1 Indication setting

Adult patients admitted to our department desiring correction of their congenital stain are first of all informed about the various possibilities in the correction of a funnel chest deformity. Usually many of them refuse implantation of foreign materials, while already informed through different media they prefer correction with autologous tissue. Some patients suffering from a small to medium defect size are selected for the transplantation of a groin-flap, predominately because of its inconspicuous donor site. Others tend to receive an abdominoplasty at the same time of tissue harvesting from the abdominal region, however this situation occurs very seldom as most of the funnel chest patients show leptosomatic habitus. Especially slim patients prefer the buttock region as the only region to gain enough tissue volume for an adequate reconstruction. In our description of the surgical technique we will focus on the FCI-flap because the groin-flap as well as the TRAM-flap are well established and documented flaps that need no further description in detail. Nevertheless both flaps will be mentioned hereby.

Groin-flap

This axial pattern flap, for the first time performed as a pedicled flap by Wood in 1862 is a frequently used free-flap even nowadays. It is based on the superficial circumflex ilium artery, dissection is easy in supine position. The flap is outlined preoperatively in an ellipse design, depending on the size required for the individual defect. The medial apex lies medial to the

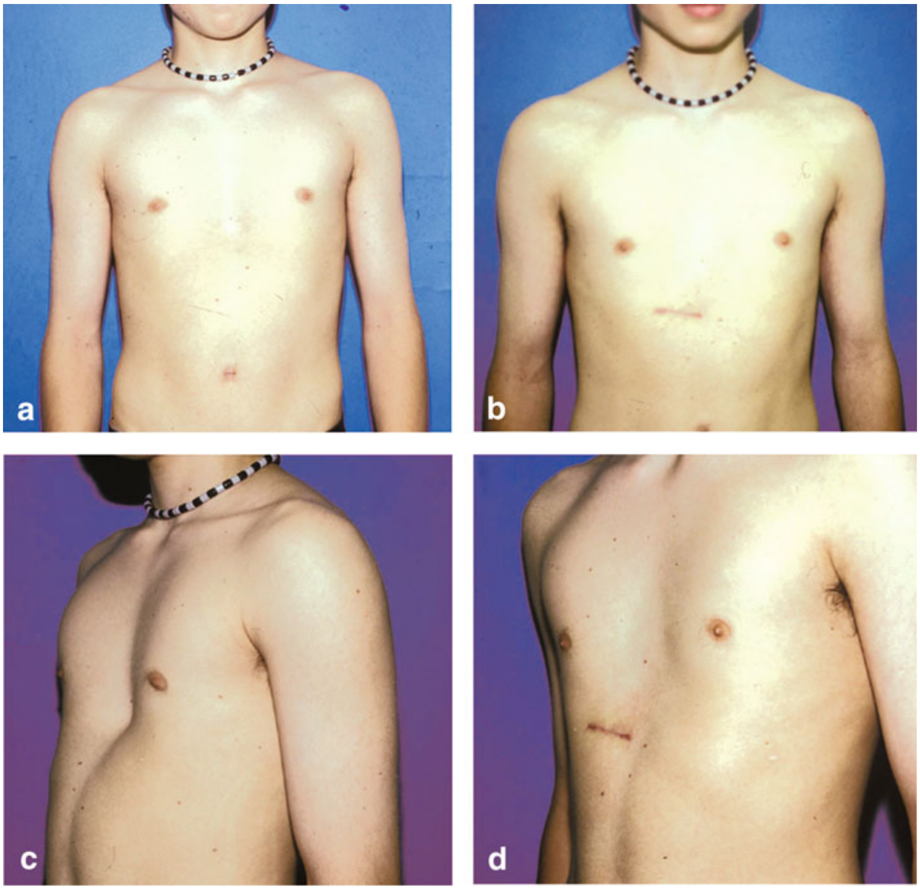


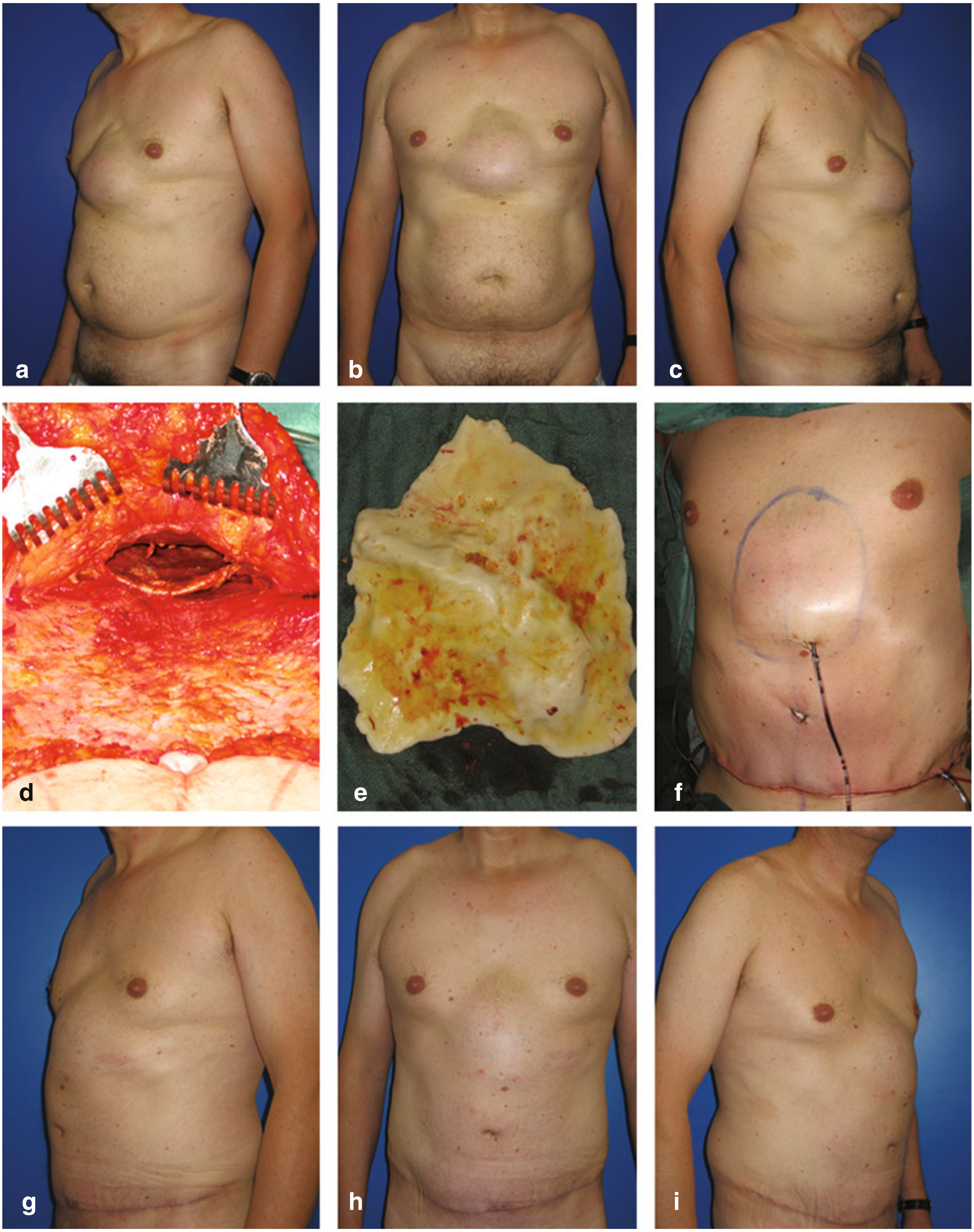
Fig. 1a. An 18-year-old male patient suffering from an asymptomatic PE. **b** Frontal view 3 months after reconstruction. Same patient before **c** and after **d** the reconstruction using the groin-flap in the lateral view

femoral vessels, the lateral apex, depending on the necessary size, may be set as far superior-laterally as the iliac spine. The flap is elevated from lateral to medial. After identification of the vessels they are followed to their origin and separated from the femoral vessels. After deepithelialization not only the flap is anastomosed to the recipient vessels with microvascular techniques and microscope, in most cases to the superior epigastric vessels, but also the internal mammary vessels may serve as recipients (Fig. 1).

TRAM-flap

This flap is a myocutaneous flap containing parts of the rectus abdominis muscle and is based on its blood supply, the inferior epigastric vessels. The TRAM-flap is frequently used as a standard procedure for breast reconstruction after mastectomy. The operation is also performed in supine position. The flap is outlined preoperatively and ultrasound is helpful preoperatively to localize the perforator vessels to the skin. Usually a muscle sparing TRAM-flap is harvested to preserve the rectus abdominis muscle to prevent hernia or bulging of the abdominal wall. For the reconstruction of a funnel chest deformity we never choose a deep inferior epigastric perforator (DIEP)-flap. Although we frequently use this flap in breast reconstruction, in a solely aesthetic indication risk factors should be minimized. It is safer to harvest and transplant a muscle sparing TRAM-flap than a DIEP-flap solely based on tiny perforator vessels.

Fig. 2. A 51-year-old man suffering from a massive capsular formation and infection after reconstruction of a PE with custom-made implants 14 years ago. **a–c** Showing the deformity before the resection of the custom-made implant and the capsular formation. **d** The capsular formation with the implant in situ. **e** Custom-made implant after resection. **f** Patient after reconstruction with the TRAM at the end of operation. **g–i** Outcome 6 months after operation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After flap elevation also this flap is deepithelialized and anastomosed to the recipient vessels at the thorax. Transplantation of too much volume in some cases required flap shaping and/or liposuction about 2 months after the first surgical intervention. Figure 2 shows a patient suffering from a massive praesternal capsular formation and seroma after subcutaneous implantation of a custom-made silicone block 14 years ago. The consecutive puncture of the seroma led to an infection making an operative intervention necessary. The resulting cavity after explantation of the silicone block and the calcified capsule was filled up with a free TRAM-flap.

Free fasciocutaneous infragluteal-flap

The FCI-flap is a fasciocutaneous-flap based on an end-artery, the cutaneous branch of the descending branch of the inferior gluteal artery [15, 16]. The size of the skin island ranges from 10 × 5 cm up to 18 × 10 cm, e.g., in patients receiving a simultaneous correction of breast asymmetry (Fig. 4a, c, e). Ultrasound of the recipient and donor vessels is performed preoperatively in all cases to identify the anatomical situation and mark the cutaneous branch of the descending branch of the inferior gluteal artery preoperatively [15]. The patient is initially placed in the prone position likewise to a buttock lift. The donor area of the subcutaneous tissue harvest will be extended cranially, laterally and caudally from the marked donor skin in the infragluteal crease (Fig. 3a). The fat pad and bursa above the ischial tuberosity is preserved and further harvesting of the flap proceeds from lateral to medial exposing the gluteal musculature. The flap vessels accompany the posterior femoral cutaneous nerve that extends into the subcutaneous fat pad and further caudally along the ischiocrural musculature. The flap vessels pass to the middle third of the gluteus maximus muscle and curse from the edge of the muscle [16]. Separation of the posterior femoral cutaneous nerve from the flap vessels can be challenging, so that dissection should proceed with loupe magnification to avoid any injury to the nerve and/or the vascular pedicle (Fig. 3b, c). After successful preparation of both structures the entire flap can be raised (Fig. 3c). To gain sufficiently long pedicle length the gluteus maximus muscle can be elevated for further vessel dissection. The vascular pedicle can be followed up to the infrapiriformis foramen by ligation of several perforators arising from the pedicle. In most cases there is a more prominent branch of the inferior gluteal artery to the gluteus maximus that originates close to the infrapiriformis foramen. Ligating this branch allows 2–3 cm of pedicle length to be gained. Thereafter, the flap's artery and vein are separated and cut off at the infrapiriformis foramen. After careful, in order to preserve to cutaneous nerves, wound closure the patient is turned to the supine position, and the recipient site at the funnel chest is prepared.

First a 5-cm skin incision is made in the inframammary crease beginning about 3–4 cm laterally from the median line. Then a subcutaneous pocket is dissected carefully in the area of the funnel depression. Thereafter, the superior epigastric vessels or the internal mammary vessels are prepared for anastomosis. Then the flap is deepithelialized, positioned into the defect and microsurgical anastomosis is accomplished. In all our female patients we were definitively successful to improve the appearance of the breast (Fig. 4). Finally, after wound closure loose dressings are applied to avoid any tension or pressure to the flap, which might swell by edema formation. That is why the pocket should provide with ample space in order to prevent self-strangulation.

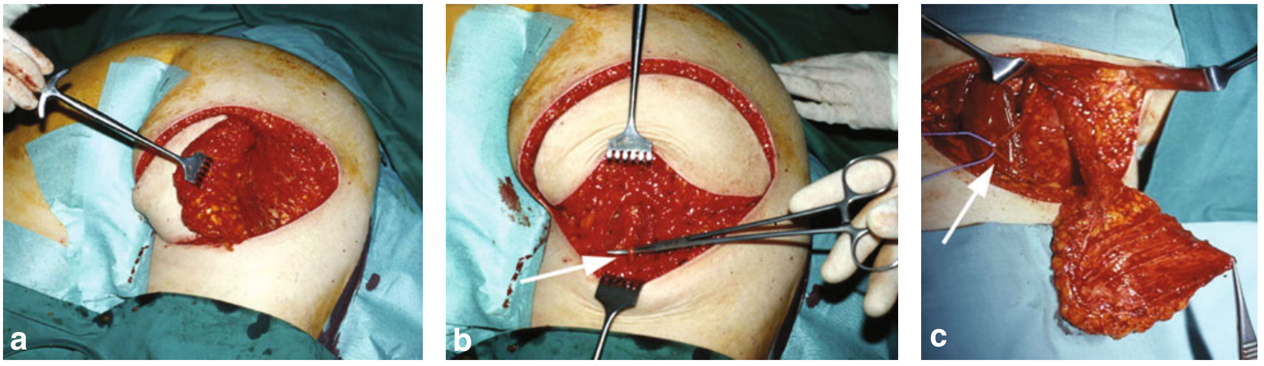

Fig. 3. Intraoperative image of a 26-year-old woman showing the preparation of the FCI-flap in the prone position. **a** Flap preparation is always started laterally. **b** Thereafter, preparation is preceded medio-caudally by identifying the border of the gluteus maximus muscle. **c** Image showing the FCI-flap before the detachment of the pedicle. Arrow is pointing to the posterior femoral cutaneous nerve

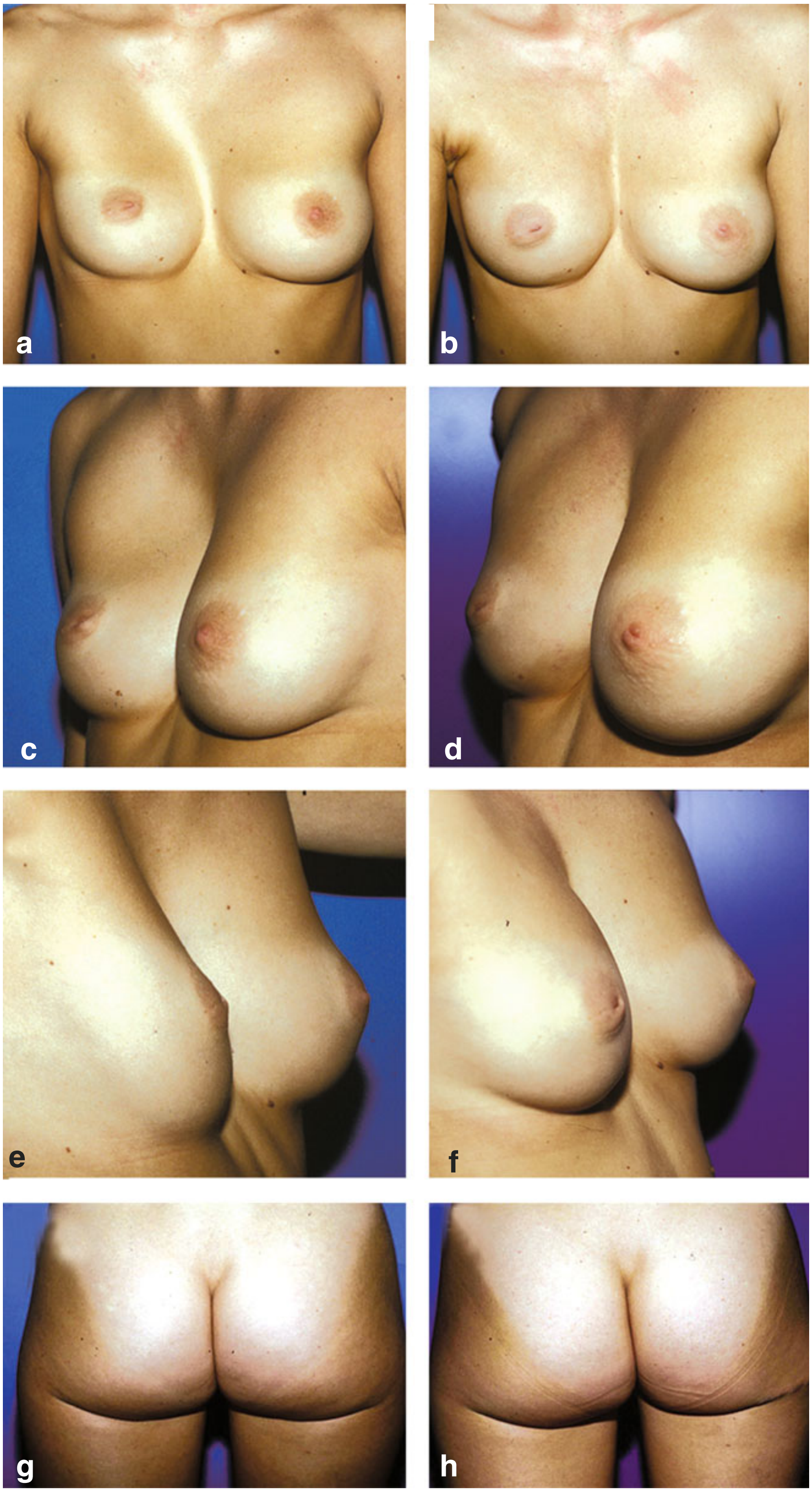

Fig. 4. Image shows the preoperative appearance of a 26-year-old woman suffering from a PE (**a**, **c**, **e**, and **g**). **b**, **d**, **f**, and **h** Images show the outcome 23 months after the surgical correction using the free FCI-flap. Note the rotation and deformity of the right breast preoperatively that is corrected completely. **h** Inconspicuous scar at the donor site

6.6.4.2 Results

A successful reconstruction of asymptomatic funnel chest deformity can be performed using autologous free-flaps from the groin, the abdominal, the buttock or the back region [17]. Operating time in our institution ranges from 210 to 320 min, in our series of funnel chest reconstruction we had no flap loss. None of the patients developed neuroma or seroma at the donor site. Infection or dehiscence of the wounds also was not observed. One patient, after harvesting of a FCI-flap, suffered from a temporary sensory discomfort at the donor site during the first two postoperative weeks that resolved completely within 6 weeks.

Patients were discharged about 7–10 days postoperatively and regularly examined in our outpatient clinic. The flaps that appeared bulky immediately after the inset, probably due to edema, retracted to the desired volume after several weeks. Nevertheless, in singular cases it was necessary to perform flap shaping and/or liposuction of the flap to improve the aesthetic appearance and reduce tissue bulk. These corrective operations were carried out about 3 months after the first operation. Finally all patients were fully satisfied with the result and would undergo the reconstruction with autologous tissue again (Figs. 1, 2, and 4).

6.6.4.3 Discussion

Congenital chest wall deformities are always challenging for the surgeon in consultation as well as in reconstruction procedures. The majority of indications for surgery in the funnel chest deformity are aesthetic and psychological reasons [1, 8]. Several techniques and among them invasive procedures, requiring fracturing and remodeling of the chest wall skeleton are potentially associated with high morbidity and high rate of complications [1–7]. These invasive procedures should be probably reserved for children with severe deformities and accompanying impairment of cardiac and pulmonary function, but still pliable bone and cartilages.

Various techniques have been described to treat patients suffering from asymptomatic funnel chest (approximately 95% of cases). Some authors described excellent outcomes using silicone implants [8, 9, 12]. Nevertheless, some patients refuse the use of foreign materials and prefer the reconstruction with autologous tissue. Therefore, plastic surgeons should offer their patients a few possibilities to find the perfect flap/tissue for the individual patient.

The FCI-flap is ideally suitable for the treatment of asymptomatic funnel chest deformity, the main advantages of this flap consist in the inconspicuous donor site scar situated in the buttock crease. A further advantage is its long vascular pedicle (up to 18 cm) that allows a wide range of motion during inset. Especially in slim patients the FCI-flap is an excellent flap because of the possibility to raise a large skin island together with the surrounding subcutaneous fat tissue. Despite taking a large amount of tissue only a mild asymmetry at the buttocks is visible during the early postoperative period that recovers over time. Our long-term experience with this flap proved that postoperative efforts should focus on meticulous hemostasis and the postoperative application of compression garments to the donor site to avoid seroma formation. Of further importance is physiotherapy to mobilize and stretch the donor site in order to regain pliability of the surrounding tissue.

Moreover, these patients should preoperatively be informed about the sitting discomfort in the early postoperative period.

Finally, in our opinion the reconstruction of the funnel chest deformity using autologous tissue offers an excellent alternative to established more or less invasive techniques with or without foreign material, however in selected patients.

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6.6.5 Free microvascular sternum turnover flap

Anton H. Schwabegger, Milomir Ninkovic

Using the so-called sternum turn-over for the correction of extensive funnel chest deformities in earlier decades, the sternum and the suspending rib cartilages were taken out of the anterior thoracic wall en bloc or otherwise lifted but pedicled at the dorsal periosteum of the sternum, were turned around 180°, and then reimplanted as a free or pedicled autologous graft [9, 10, 28]. Bone resorption in these turned over but non-vascularized tissue grafts [27, 28] leads to inevitable recurrence and therefore were major drawbacks of these procedures. Loss of elasticity of the thoracic respiratory function, caused by fibrosis of cartilage remnants, infection, or dislocation of the implants and thus unimproved physical condition [5, 7, 26] or undesired aesthetical appearance resulted. This was especially problematic at the age beyond childhood, when revascularization and nourishment through embedding tissue were not sufficient any more for viable reintegration of the turned-over tissue.

On the basis of these disadvantageous results, some authors turned over this skeletal tissue block 180° as well, but not only based on the sternum periosteum, but also particularly pedicled at both internal mammary (thoracic) vessels [8–10, 25, 26]. The cross-over of both vascular pedicles, caused by such a turn-over procedure, on the one hand was advantageous for the genuine blood circulation within the graft; however, on the other hand it caused relative shortening of the vessels along the median centerline on the basis of twisting and thus shifting of the sternum and adjacent rib portions cranially, not beneficial for the purpose of thoracoplasty. Until now this method is described solely in single case reports, and long-term observations are lacking so far.

However, and on the basis of further developments in microsurgical techniques, for this type of thoracoplasty nowadays a method of microvascular turn-over of the sternum and adjacent ribs is available [7, 13, 26]. The revascularization of the 180° turned around osteo-chondro-muscular composite graft logically leads to much improved viability of such tissue than it would do without own perfusion. Within small children, this kind of sternum turn-over without revascularization may lead to “graft take” of still very thin skeletal structures yet, but in contrast to that in the adult such a “graft take” is unfeasible in any case. Based on the size and large volume of tissue block such a procedure inevitably leads to necrosis with ensuing absorption, under circumstances even to hazardous infection and furthermore to inevitable recidivation of the funnel deformity.

In addition to these above-mentioned techniques several others are available for the remodeling correction of pectus excavatum, which is in the case of any necessity for expansion of the thoracic cavity in order to improve cardio-pulmonal capacity [1, 3]. The most popular and very established method relies on the MIRPE technique, previously developed by Donald Nuss [14], with implantation of a specially formed metal strut using a minimally invasive access under videoendoscopic control (VATS, Chapters 5.4 and 6.3), but without the necessity of osteochondotomies.

In many cases with rigid skeletal thoracic structures, a method further developed from the method of Nuss and out of earlier methods may also be applied in combination with a semi-open access (MOVARPE, Chapter 6.1 until 6.4).

Above all in adults, the Ravitch method [16] that is without metal strut suspension of the remodeled anterior thoracic wall tissue may lead to relapse in up to 36% [2, 14]. Also established alternative methods [1, 17–19] can lead to relapse, if the supportive metal struts do not remain sufficiently longer in situ or the adolescent or adult thorax has matured to an already too rigid structure that withstands simple internal strain.

The osteochondroplasty or the sternal support with metal struts, combined with a minor open access (MOVARPE, Chapter 6.4), that is with multiple osteotomies and chondrotomies to relief a rigidly formed funnel, may cause extensive fibrosis and scarring in the area of the remodeling. Such fibrosis, if the operation was carried out already at an early age, on the one hand can lead to growth interferences and therewith to an unpleasant deformity of the anterior thoracic wall. As a worst result such scarring may even inhibit further growth of the anterior thoracic wall, but with the thoracic spinal column still growing leading to countervailing kyphosis of the back [4]. On the other hand such extensive fibrosis and scarring can frustrate the attempt of success of the expansion of the thoracic cavity also in adults. Such auto-reparative processes diminish any elasticity within the area of remodeling, so that the therapeutic effect of an improvement of cardiopulmonal function will be impeded therewith [4].

In rare cases with nickel allergy, several different methods containing the procedure of metal strut implantation for temporary suspension of the anterior thoracic wall are not applicable. The manufacturers offered preformation of unbendable nickel-free titanium bars, but they were not practicable especially in adults due to the lack of bending properties, which particularly led to hazardous maneuvers during their removal. Especially in such selected cases the microvascular turn-over technique presents itself as an alternative to circumvent these problems and will be described now in the following.

Ishikawa in 1988 and Chen in 1999 already performed the microvascular sternum turn-over in several cases; Ninkovic in 2002 also presented a small series of selected patients treated with that complex procedure [8, 13, 26]. Through this turn-over of 180°, the existing depression of the sternum is directly converted into an elevation indeed. That artificially emerging keel chest deformity at this composite graft has to be now flattened by multiple chondrotomies, so that an aesthetically appealing result is formed. This procedure moreover yet expands the thoracic cavity and still maintains the elasticity between rib cartilages and sternum, the sternocostal joints, which are synchondroses and diarthroses (Chapter 2.1). Attributable to that microvascular revascularization of the turned-over part of the skeletal thoracic wall, necrosis will be avoided and therewith effects of extensive absorption or fibrosis are absent, so that elasticity necessary for the respiration movements remains preserved. During that surgery parasternal rib cartilages are cut but not resected and the required sternum osteotomy subsequently is fixed in the sense of an osteosynthesis with absorbable material [23]. This kind of osteosynthesis, applied with diligent technique, should lead to physiological bone healing with only slight callus formation. Additionally securing sutures at the rib transsections support the chest stability.

6.6.5.1 Indication setting for that kind of surgery

Based on the yet existent invasiveness and the long duration of such a microvascular intervention, this kind of remodeling is rather reserved for the adolescent and adult patients. However, this indication is valid only if cardiopulmonal restrictions exist and the patient rejects alternative methods or other distinct reasons exclude the use of a metal strut (e.g. nickel allergy, refusal of metals in the body, or multiple preceding intervention). Indication setting for such an intervention is postponed after a psychological investigation, a 3D-CT-scan as well as a medical investigation of circulation and pulmonary functions (Chapter 3.5). Only then and also after careful and extensively conducted informed consent with the patient, this intervention is carried out on an interdisciplinary basis and jointly with a thoracic surgeon. Prerequisites are however abundant experiences with the microvascular technique. Above all exact knowledge and experiences with the internal mammary (thoracic) vessels are also required, for example in microvascular breast reconstruction as with free flaps [6, 11, 12, 20–22].

6.6.5.2 Surgical technique

The presternal skin incision can be made like a lazy S or inverted Y (Fig. 1a and b), which alleviates the access and the exposition of the sunken sternum. This shape finally yet leads to a swung but optically short scar, which occupies only a small area at the anterior thoracic wall. Both pectoralis major muscles are elevated from the sternum and the rib cartilages including small margins of sternal periosteum for the purpose of reinsertion after completion of the skeletal remodeling process. In appropriate manner also the insertions of the rectus abdominis muscles and the linea alba are meticulously elevated from the xiphoid and the inferior rib edges. Subperichondral resection of 1–2 cm of rib cartilages along the depression region now follows until the area where the sternum declines backwards. Exactly here and after relief of perichondrium as well as intercostal muscles the internal thoracic vessels are carefully dissected free and prepared for microvascular anastomoses. However, the backward angulation of the costal cartilages at the sternal margin allows only limited exposure and therefore complicates the microvascular anastomoses [15]. That is why experience in the microsurgical techniques is absolutely mandatory, because also the respiration movement lets vessel suturing under microscopic view become a severe endeavor.

Especially in these patients requiring such sophisticated kind of remodeling, the access to the vessels is usually located at the level of the second or third rib. From cranial to caudal, the rib cartilages and the intercostal muscles in the area of the funnel depression will be transsected. The thoracic surgeon now carefully mobilizes the intrathoracal mediastinal structures and organs from the back of the sternum and rib cartilages. If feasible, the parietal pleura is dissected carefully from the osteochondral thoracic wall block, without opening the pleural cavity, which means an advantageous epipleural dissection. With regard to avoidance of pleural

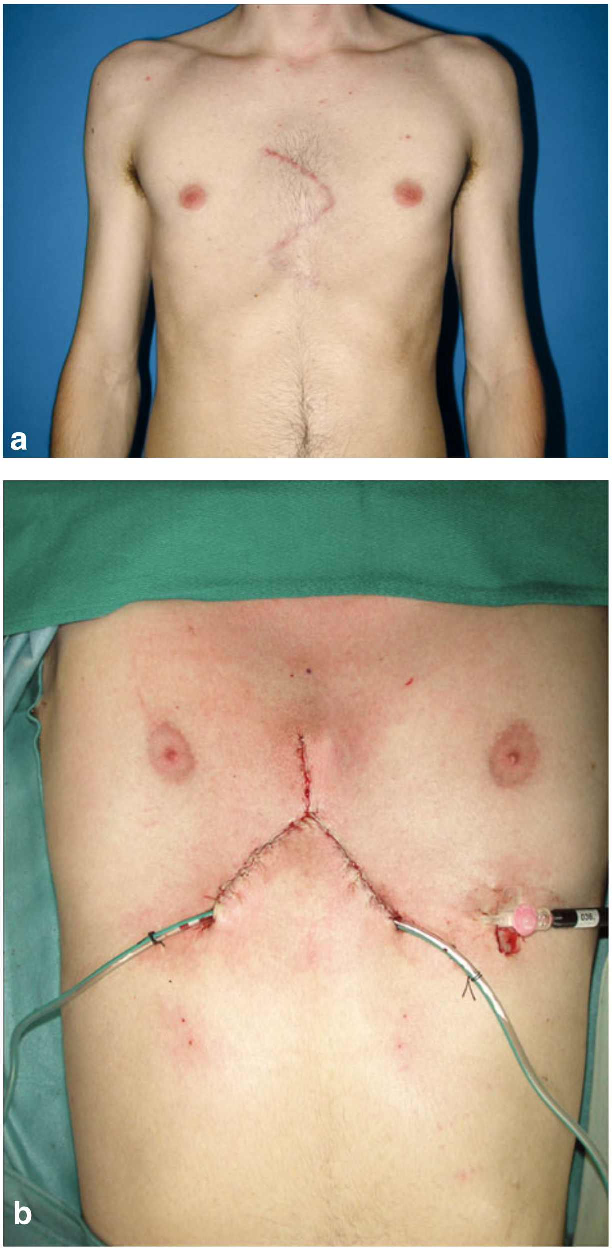

Fig. 1a. Alternatively used curvilinear incision for a better survey of the area of remodeling and the important zone of microvascular anastomoses at the right side at the level of the second intercostal space in this case. **b** An inverted “Y” incision may suffice, if the access for microvascular anastomoses due to advantageous anatomical situation of the deformity may be placed more caudally. Notice pO_2 probe at the left side

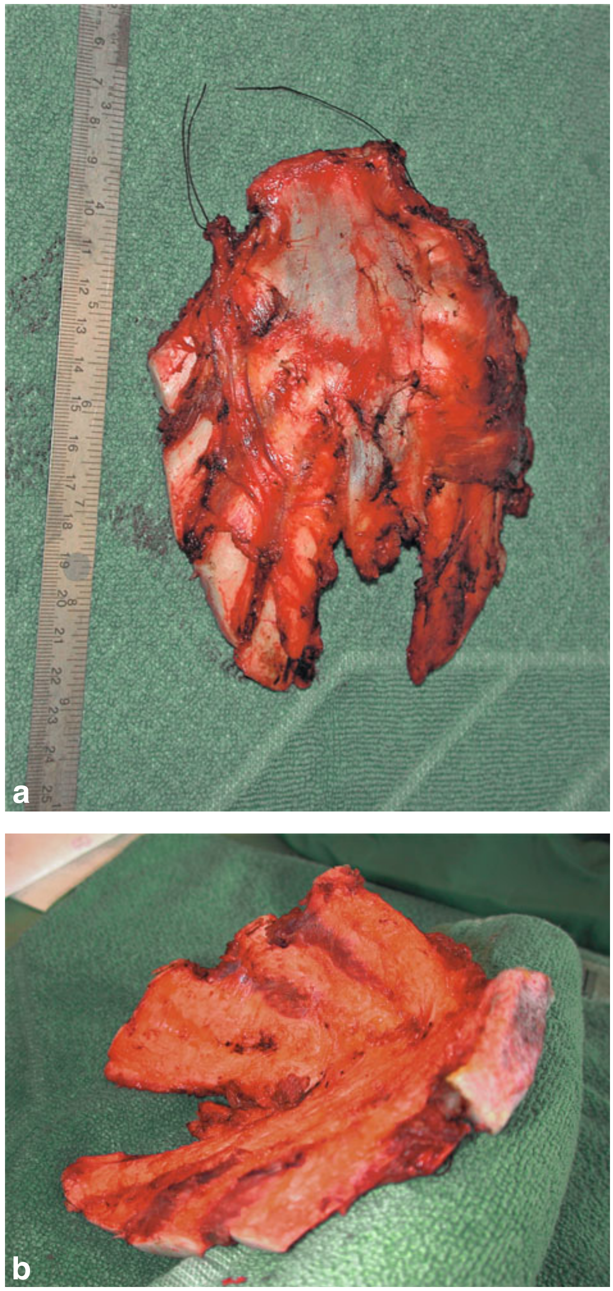

Fig. 2a. Harvested composite flap, containing the inferior thirds of the sternum, the adjacent ribs (four to seven bilaterally), and the internal thoracic vessels as the microvascular pedicle prepared for anastomoses, marked with a suture. View from dorsal. **b** Similar specimen, view from an aspect cranial and the funnel faced anteriorly

leakage and ensuing danger of pneumothorax and/or hematothorax, the integrity of the parietal pleura should be preserved unconditionally. After mobilization of the sternum-rib cartilage-block now follows the preparation of the internal thoracic vessels, so that on one side the recipient vessels and on the other side the donor vessels of the so-called ostoechondral flap are dissected with some excess of length. The surplus of vessel length herewith is necessary to provide with sufficient length of tissue for manipulation after the turn-over procedure (Fig. 2a and b).

After the vessel preparation, the sternum will be cut horizontally with an oscillating saw at the level of the corresponding intercostal area. The circumcised block containing the sternum and its adjacent rib cartilages is now elevated as a free flap (Fig. 2a and b) and is turned around 180°, with the inner surface now turned outwards. In order to avoid the now artificially created keel deformity resulting from that turn-over procedure, single chondrosternal synchondroses and diarthroses can be resected, if necessary for appropriate remodeling. However, some of those spurious joints must be preserved in order to maintain sufficient elasticity for respiration movements. To maintain adequate elasticity, parasternal chondrotomies should be carried out primarily and prior to any flexible joint resection. Especially during these manipulations, the internal thoracic vessels must be protected with extreme caution, since only these vessels are capable of maintaining viability of the turned-over graft. To secure now the molded physiological flat contour of the turned-over skeletal tissue flap, absorbable osteosynthetisis plates can be mounted at the docking areas of the transsections of the rib cartilages (Bionx^{TM} Implants, Tampere, Finland).

At the site of sternum osteotomy absorbable synthetic material is also used in order to obtain a solid osteosynthesis (Figs. 3a and 4). The corresponding rib cartilages are fixed with PDS mattress sutures thereafter in order to obtain additional parasternal lateral stabilization. Now the internal thoracic vessels of the turned over graft are anastomosed to the recipient vessels in microsurgical technique and with the aid of an operation microscope. The setting of anastomoses is possible only at the side where surplus length of the vessels is prepared. Because this microvascular turn-over is a matter of a buried flap, a pO_2-probe (Licox-GSM, Kiel, Germany) or similar device has to be implanted in order to enable continuous measurement of the vascularization and thus viability during the first postoperative week (Fig. 1b). In the rare case of impaired perfusion, the potential complication of tissue loss may be recognized timely and appropriate microvascular revision can be performed [29].

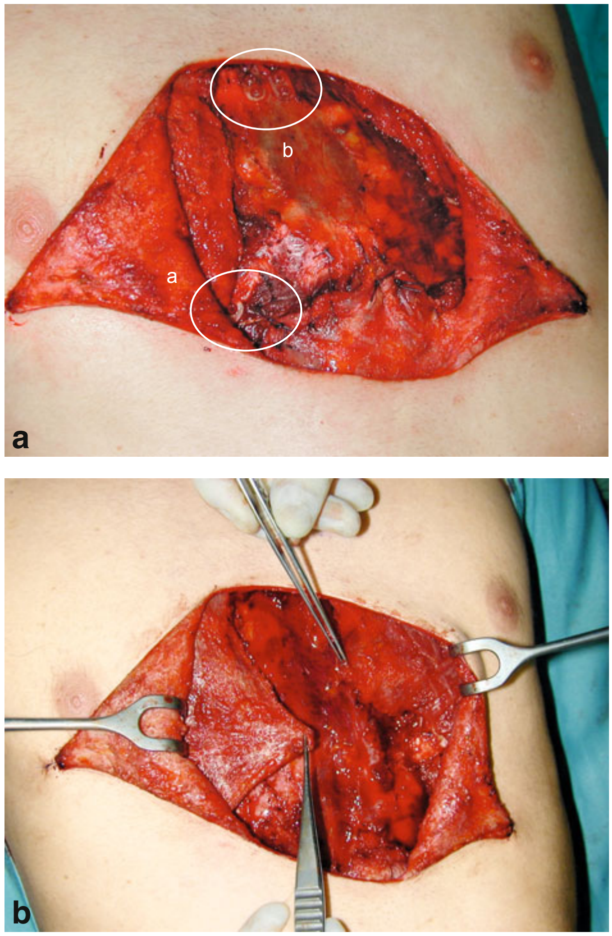

Fig. 3a. The turned-over composite flap already turned over and revascularized by microanastomoses to the internal thoracic vessels, prior to muscle flap reposition and wound closure. Circles show bio-absorbable osteosynthetic material at the rib cartilages (*a*) and the sternum (*b*). **b** The previously elevated pectoralis muscle flaps are anatomically repositioned and tightly fixed to the posterior sternum periosteum

Subsequently the careful anatomical repositioning of the elevated pectoralis (Fig. 3b) and rectus abdominis muscles is then performed at the sternum to the periosteum as well as to the perichondrium of the ribs. Now, due to the turn-over procedure, the internal thoracic vessels are ventrally exposed, particular caution has to be paid during the anatomical refixation of muscle with seaming sutures along the course of the vessels. Herein compressing seams must be avoided in the environment of the vessels in any case. For the case of any pleural lesion during the flap harvest, the use of a chest tube is recommended. The implantation of a chest tube is

Fig. 4. Solid osteosynthesis of the sternum at the level of the second intercostal space, 6 years after the turn-over procedure

meaningful anyway in order to divert seroma formation, pleural effusion, or even hemorrhage, which is to be expected in such invasive interventions with moderately high incidence and must not be neglected.

6.6.5.3 Discussion

The non-vascularized sternum turn-over described by Wada [28] in any case is not suitable in the remodeling of an adult thorax because the very large tissue block cannot sufficiently become revascularized through the covering soft tissue. The unavoidable consequence would mainly be necrosis and major tissue absorption, in further consequence also potential infection of the large skeletal tissue block and therefrom-resulting further complications. Such an expanded dissection and devascularization of tissue with ensuing absorption processes then will lead to an expanded fibrotic scar pad, which definitely restricts the pliability of the anterior thoracic wall [4]. Based on such pathologic processes to be expected and seen in a long-term aspect, a non-vascularized sternum turn-over appears to be a clear contraindication for tall or athletic adolescents and adults. The alternative and further developed method of the microvascular revascularization of turned-over tissue leads to a rather physiological healing process with much less development of expanded scars. Furthermore, the sternocostal junctions remain viable thus maintain their function, because absorption processes hardly occur. However, and so far no larger series of the microvascular sternum turn-over technique excepts minor clinical series [7, 13, 26] may be found in the available literature. This is possibly true because well-chosen expertise and narrow interdisciplinary cooperation with thoracic surgeons must meet and meanwhile alternative, less invasive methods are established and were further developed.

Through the development of the minimally invasive (MIRPE-) method according to Nuss [14], many patients sooner and rather decide to undergo this minimally invasive intervention. Above all if the funnel is present flat and less marked, the MIRPE method appears the most advantageous. The microvascular sternum turn-over however is rather subject to complications based on its invasiveness why as an early complication pneumothorax, hematothorax, infections, or the danger of the complete flap loss may appear. Especially because of the consequences of a possible flap loss, extensive microsurgical experience is a prerequisite in order to reduce herein the technically involved possibilities of any complication to the most minimal. Possible and until now only in individual cases observed long-term complications exist [24], namely instability of the osteosynthesis and the chondrocostal sites of coaptation. Thereby on the one hand callus formation at the posterior surface of the sternum (Fig. 5) may develop and on the other hand through dislocation of cut rib ends

Fig. 5. Persistent callus formation at the posterior level of sternum osteosynthesis, prone to cause adverse hemodynamic effects on the greater vessels and heart

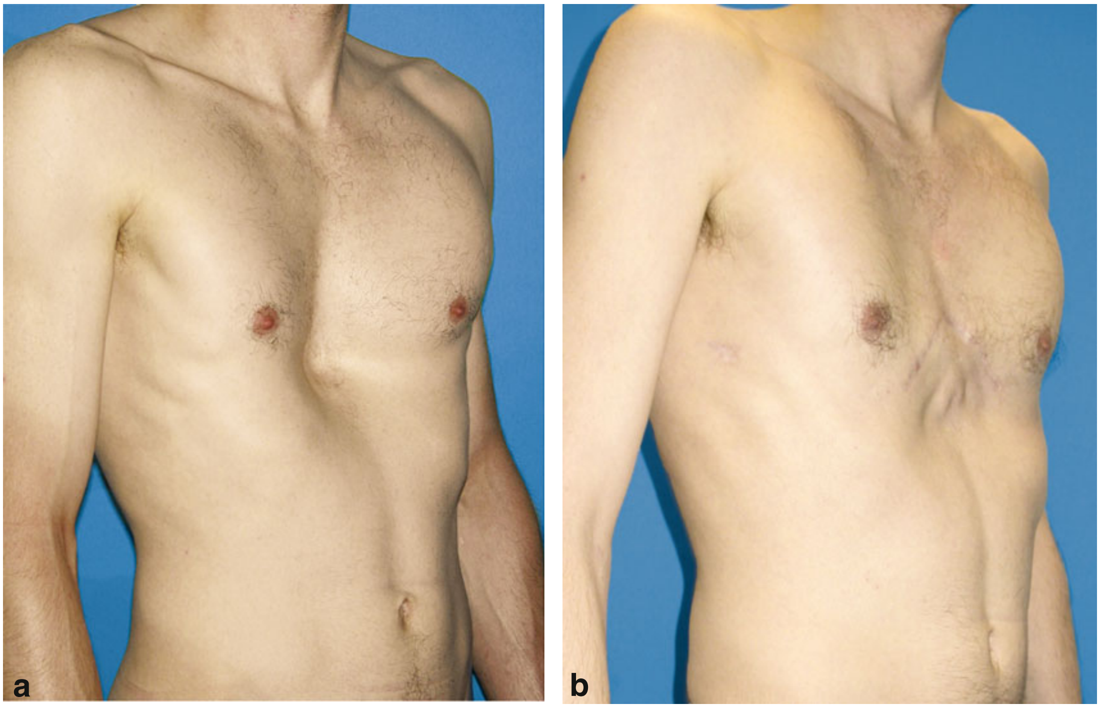

Fig. 6a. 30-Year-old male with moderate cardiopulmonal impairment due to the funnel chest deformity, prior to surgery. **b** Situation 26 months thereafter with stable and rigid anterior thoracic wall and improved aesthetic appearance

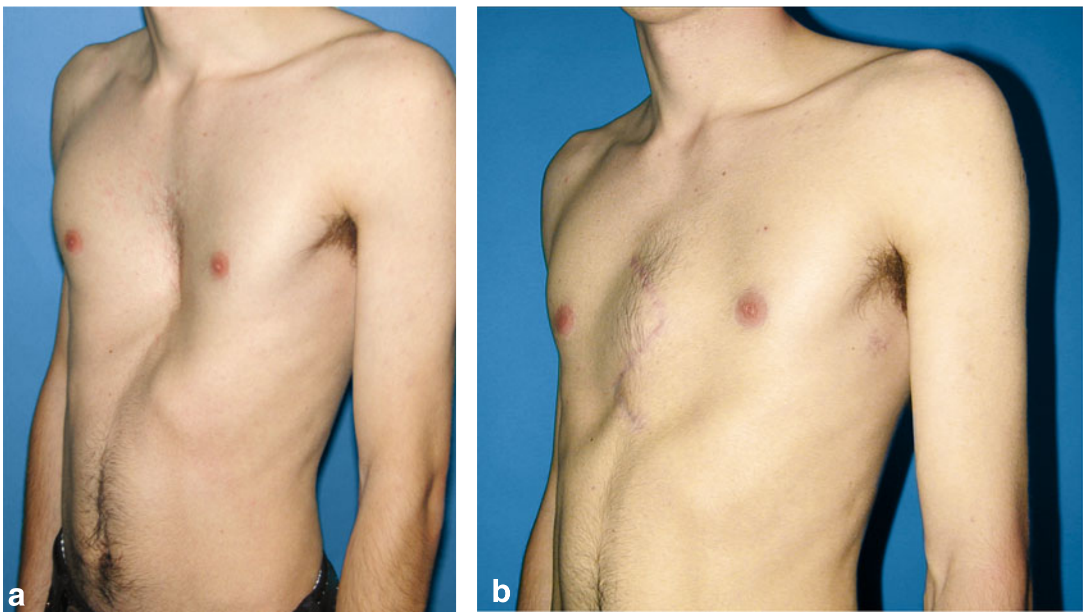

Fig. 7a. 22-Year-old male with sternal depression causing moderate cardiopulmonal restriction. **b** Situation 6 months postoperatively, with inadvertent overcorrection resulting in a slight sternum hump, however, the patient felt very content with that result

compression of the large vessels and the ventricles (Fig. 8b) with potential effects on cardial hemodynamics may follow.

In the few case series described until now [7, 13, 26] the long-term results in regard to aesthetics are described as excellent (Figs. 6a,b and 7a,b). Long-term investigations with regard to alteration or improvement of the cardiopulmonal function or other morphological long-term consequences are not reported up to date. In the own patient series, two patients after a long-lasting period without problems and first after several years complain chronic pains in the surgically involved area of the parasternal end branches of the intercostal nerves. Through the worldwide triumph of the MIRPE technique method, the further development of the microvascular sternum turn-over flap, based on its invasiveness, the required surgical expenditure and the necessity of an extensive microvascular expertise receded into the background. However, indications can still remain, above all in the asymmetrical cases, when the MIRPE or other methods of suspension with or without metal strut will not suffice for the desired shape of remodeling. Especially in unilateral hypoplasia of the thoracic wall, suspension techniques with the pectus bar are not feasible to improve symmetry. They cannot be successful, because the important suspension point for the bar, which should carry the mobilized sternum, is situated too deep at the site of concern. Such an augmentation of a unilateral depression of the anterior thoracic wall appears only feasible through remodeling in the sense of a skeletal tissue exchange from the one to the other side.

The only meaningful and practicable alternative herein exists in the microvascular turn-over because it more or less exchanges the pseudo-surplus of autologous viable tissue from the one side to the hypoplastic other side of the thorax and symmetry assimilation takes place (Fig. 8a and b). Particular care has to be applied in order not to harm the end branches of the intercostal nerves and to avoid the late complications of cumbersome nerve stump neuromas.

For the case that a very steep and deep funnel deformity in adults is present, nowadays the method of the MIRPE combined and modified with a minor central open access offers itself (Chapter 6.4, MOVARPE technique). In contrast to the microvascular sternum turn-over however, two interventions are necessary, on the one hand the suspension of such in parts invasively remodelized thoracic wall by means of an implanted pectus bar and on the other hand its explantation a year or more thereafter. The comparative invasiveness of the MOVARPE technique and the cumulative duration of

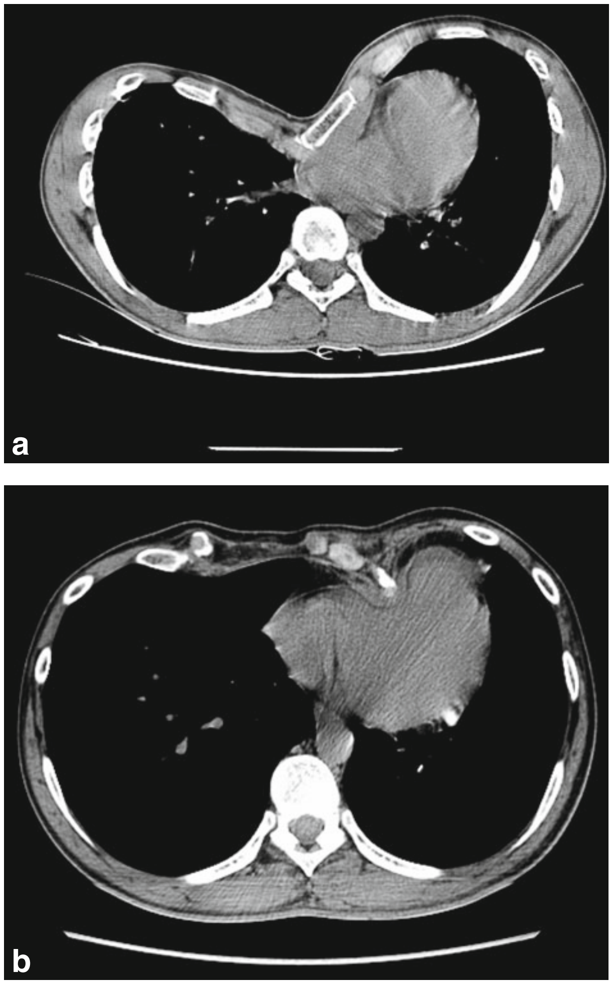

Fig. 8a. Unilateral asymmetric depression with sternum malrotation and reduction of anterio-posterior diameter at the affected side of the thorax, an ideal indication for the turn-over procedure. **b** Same patient as in **a**, 7 years after the sternum turn-over procedure. The cut and refixed ends of the ribs seem to cause an impression at the cardial ventricles with a compressive effect to them, but could not be verified through cardial sonography and functional testing (according to Chapter 3.5). Notice the excellently achieved symmetry of the thorax diameters

the morbidity of both interventions vis-à-vis the microvascular turn-over technique appears likewise pains taking for the patient. A comparison of both methods however is not yet possible to date based on the low case numbers of these techniques.

Though it appears that still indications remain to apply the microvascular sternum turn-over, in priority the desire of the patient for a single intervention, the refusal of metal implants, or objection to multiple scars, but in particular in an extensively and asymmetrically shaped thoracic wall. It must be considered

Fig. 9. Exemplary case with unilateral and deep depression, massive sternum malrotation and rather not suited for the MIRPE procedure. Alternatively to a suitable MOVARPE procedure, the microvascular sternum turn-over procedure may also serve to improve this situation

indeed in girls and women that herewith a large visible scar stains the zone of the décolleté then. Therefore, the utmost remaining clear indication seems to be the distinct asymmetrical and unilaterally deeply shaped extensive funnel chest deformity in males with proven cardiopulmonal restriction (Figs. 8a and 9). Hereby the previously described experiences are based however on smaller series and further prospective studies with this kind of surgical correction are needed for the consolidation of such an indication setting, however, being well considered and with an informed consent thoroughly elaborated.

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6.7 Combined surgery with associated anomalies or disease

Anton H. Schwabegger

The most frequent and therefore most important monogenic syndromes that go along with pectus deformities are Marfan syndrome, Noonan syndrome, and disruption sequences like Poland and Moebius anomaly as well as genetic associations in exemplarily the Pentalogy of Cantrell (Chapter 2.2).

Pectus excavatum is a hallmark in Marfan syndrome. Pure Marfan or marfanoid features (Fig. 1a–f) are more frequent in the female population and a high percentage, between 50% and 70% of all of them develop mitral valve prolapse [4]. Although stated by Arn in 1989 [1] that Marfan patients operated on pectus excavatum deformities show more relapses, Redlinger in 2009 contradicted this statement on the basis of 246 patients treated so far. Redlinger and co-workers concluded that Marfan and marfanoid patients show a higher complication rate concerning wound healing, which was attributed to connective tissue disorders. There was no difference in clinical outcome of pectus excavatum repair of Marfan or marfanoid versus patients without such disorders in terms of relapse or patient satisfaction. However, usually and probably based on connective tissue disorder the severity of the excavatum deformity in the Marfan and marfanoid collective is higher, requiring more invasive remodeling in the sense of implantation of multiple pectus bars. There is lacking evidence so far, if Marfan and marfanoid patients with a more severe deformity with respect to cardiopulmonal function would benefit more from remodeling surgery than the non-marfan counterparts. However and without evidence, Redlinger and co-workers in their report conclude that the patients felt much better than before surgery. This effect might be based on a psychological effect solely, since pectus

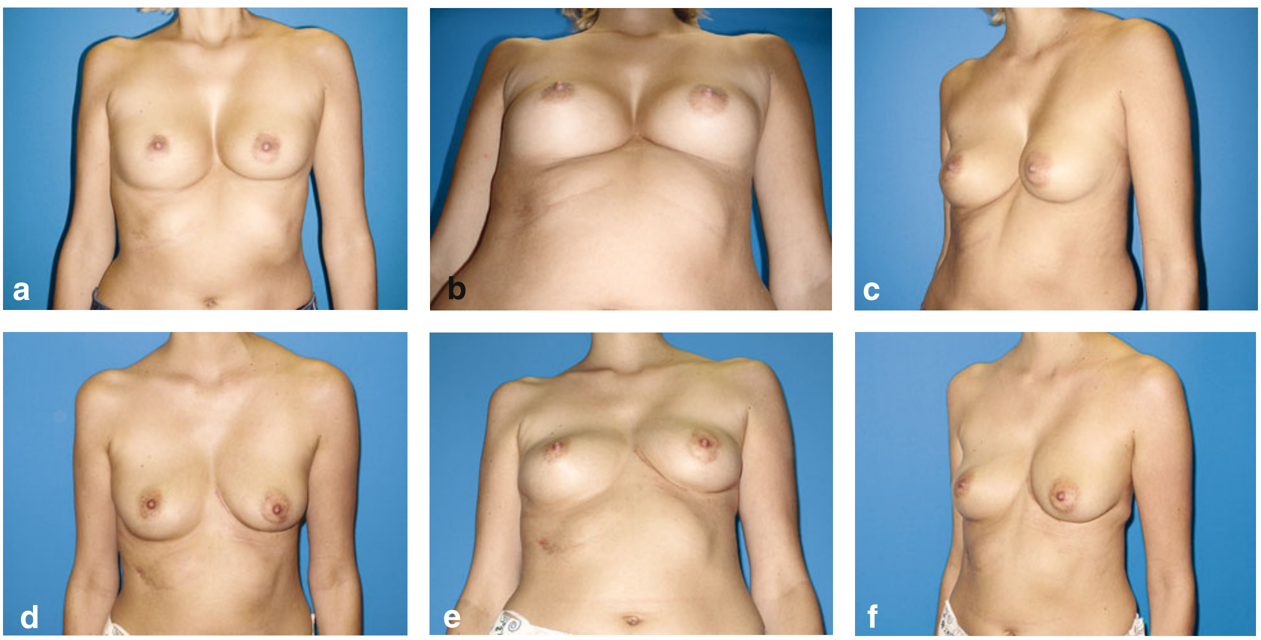

Fig. 1a–c. 26-Year-old tall female with pectus excavatum, marfanoid features, and vertebral scoliosis. **d–f** Same patient, 6 months after implantation of one pectus bar and remodeling via a minor open videoendoscopically assisted repair (MOVARPE)

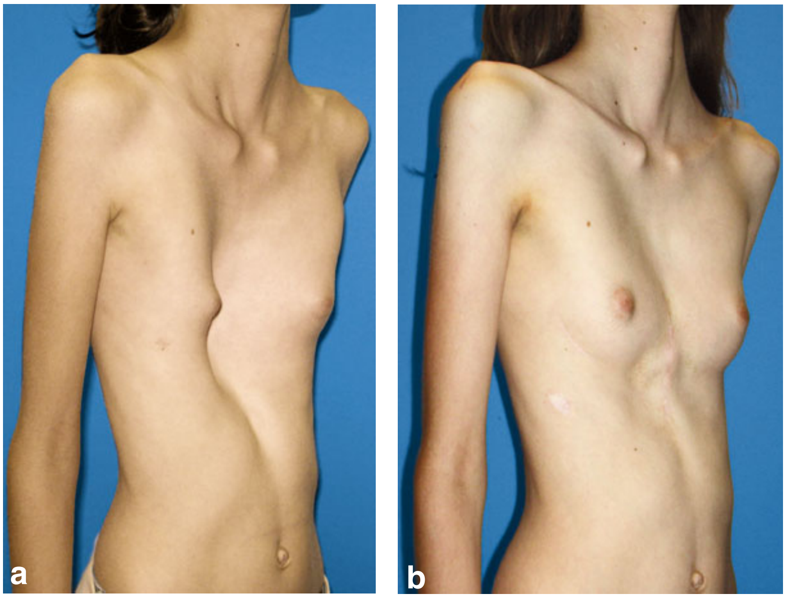

Fig. 2a. 13-Year-old female with severe pectus excavatum deformity and Marfan syndrome. **b** Same patient $1^1/_2$ years after correction with implantation of one pectus bar and the MOVARPE procedure

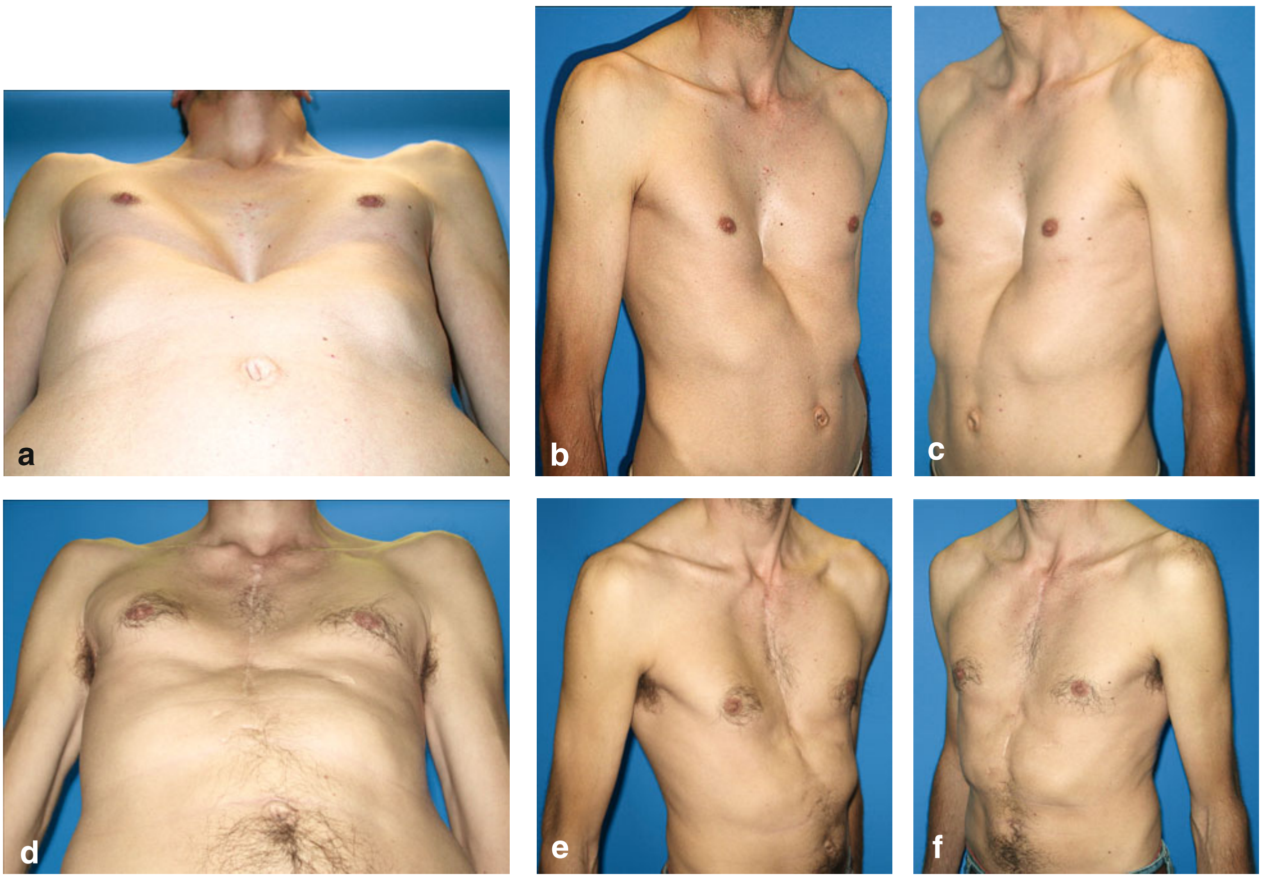

Fig. 3a–c. 38-Year-old male with mitral valve insufficience based on the pectus excavatum deformity. The patient and the thoracic surgeon at the time of cardiac surgery requested simultaneous repair of the deformity to widen the intrathoracic space. **d–f** Same patient 4 years after simultaneous mitral valve and pectus excavatum repair with a modified Ravitch procedure and osteosynthesis with bioabsorbable plates

excavatum deformity in slim and leptosome Marfan or marfanoid patients additionally due to lacking subcutaneous fat tissue presents more dramatically and the results of remodeling procedures therefore seem to be more impressive (Fig. 2a and b) than in non-marfan counterparts.

Occasionally patients with Marfan or marfanoid phenotype present first with the need of cardiac surgery at a higher age. Until then these patients do not bother about their deformity and thus required no remodeling surgery. At the time when cardiac surgery is indicated, exemplarily due to mitral valve insufficiency, the pectus excavatum deformity may be corrected simultaneously. Such a simultaneous approach may even be advantageous for the cardiac surgeon, as a wide exposure of the heart after rib cartilage resection, multiple chondrotomies and sternum osteotomies loosens the severely deformed anterior wall complex, which alleviates the surgical access to the heart [2–6]. A median sternotomy with multiple parasternal chondrectomies at both sides is done. One or multiple horizontal sternotomies are performed to elevate the bony depression for a superior exposure to the usually dislodged heart and intrathoracal organs [5]. After completion of ensuing heart surgery, the remodeling process follows the principles of Ravitch with reefing sutures of the perichondrium tubes. The procedure may be modified in utilizing bioabsorbable plates and screws to refix the osteotomized sternum (Fig. 3a–f). Conventional steel wires, if necessary may secure the fitting. However in the pectus excavatum deformities overabundant length of the rib cartilages and perichondrium tubes allows an almost tension-free closure of the median sternotomy. Such absorbable osteosynthetic material is preferably used because in the case of sudden intrathoracal complications an immediate uncomplicated surgical access is feasible, which would not be the case after utilization of metal plates. Even resuscitation will not be impeded by the malleable biological plates, which on the other hand could become an endeavor in the presence of heavy metal hardware [7]. If a patient must undergo secondary interventions at the heart years later, it might be fraught with technical difficulties due to scar adhesions in an untreated funnel deformity and survey is impeded by the still present sternal depression. The additional remodeling procedure herein requires approximately one additional hour in addition to the time taken for heart surgery. On the other hand, wide exposure through the remodeling access allows a more secure intervention for the cardiac surgeon thus such a simultaneous repair is justified, in addition also with regard to the long-term benefits [5].

The Noonan syndrome phenotype is characterized by normal measurements at birth, short stature later in life, congenital heart defects with most frequently pulmonary valve stenosis and/or cardiomyopathy, broad or webbed neck, pectus arcuatum (Fig. 4a and b), cryptorchidism, coagulation defects, and facial dysmorphisms such as ptosis, wide-spaced eyes, and low-set and posteriorly rotated ears. The surgical correction of such a mixed deformity of the anterior

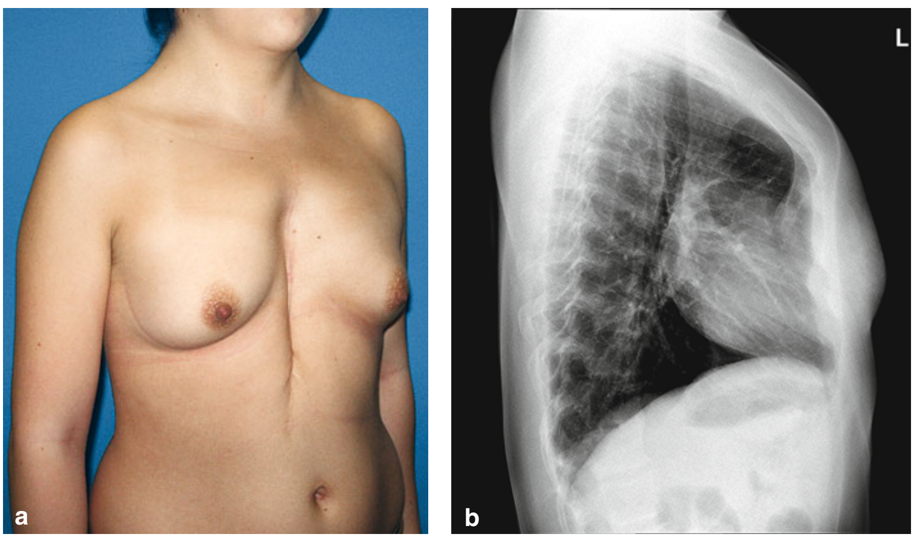

Fig. 4a and b. 21-Year-old female with Noonan syndrome after cardiac surgery in early childhood. Also note phenotypically broad webbed neck and multiply arcuated sternum thoracic wall called pectus arcuatum deformity is described in detail in Chapter 8. Occasionally these patients require plastic surgical treatment for their additional anomalies also.

The extremely rare coincidence of pectus excavatum and gynecomastia may be purely accidental. However the scar that is produced by subcutaneous mastectomy may simultaneously serve as a surgical port to implant a custom-made silicone block via subcutaneous tunnel to fill up the depressed sternal area (Fig. 5). On the other hand and for the case of timely different occurrence of the tumor, the implantation scar may serve for the mastectomy procedure if primarily set in an advantageous area.

More frequently asymmetric deformities at single ribs are present in coincidence with a pectus excavatum deformity (Fig. 6a). If located advantageously and if requested by the patient, the aesthetic correction of isolated rib humps simultaneously with silicone implantation may be managed from the same incision that is primarily placed above the protruding ribs. From the same incision, and after completion of cartilage and rib bone resection, a subcutaneous tunnel is created to implant the silicone block (Fig. 6b and c).

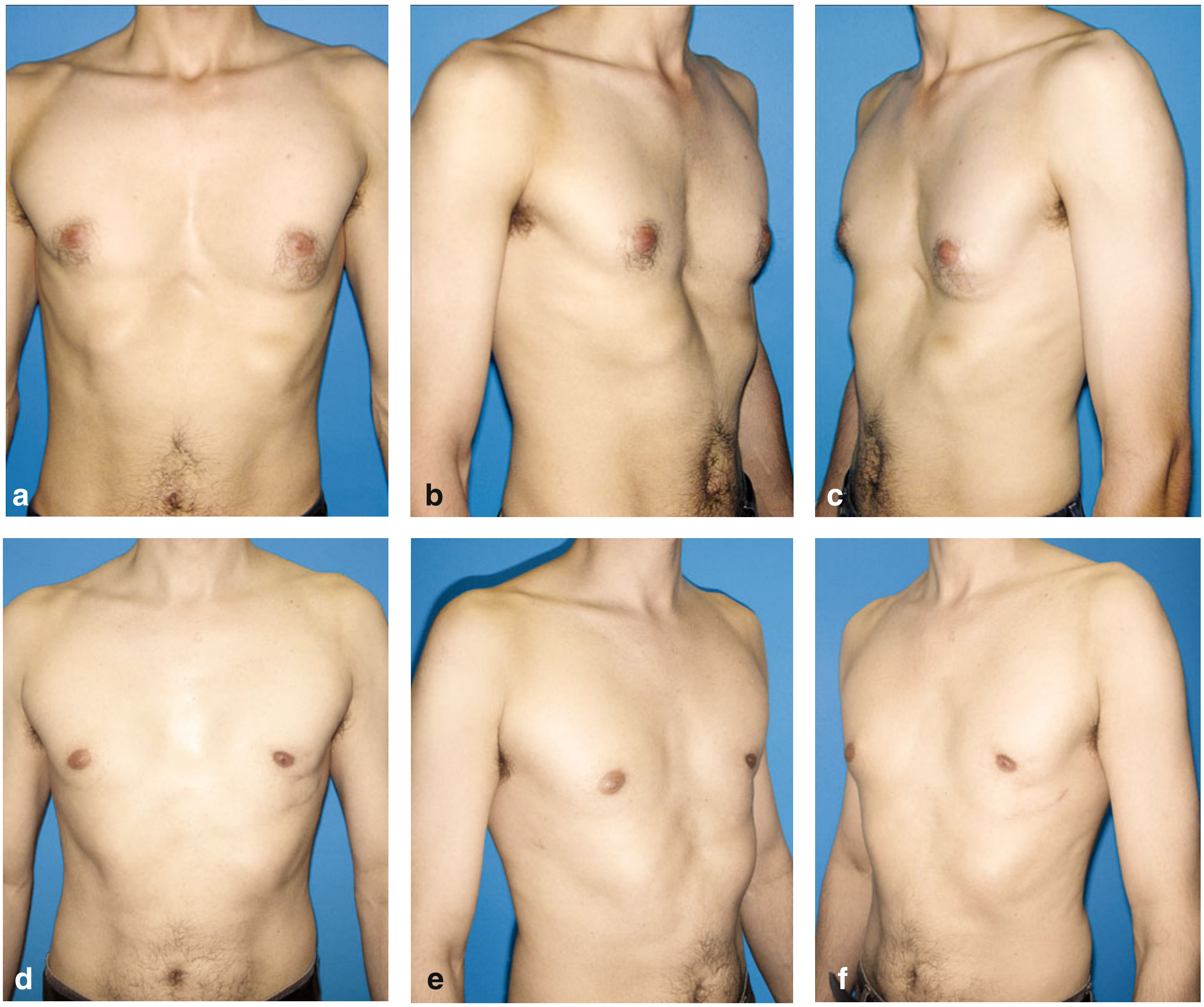

Fig. 5a–c. 25-Year-old male with a unilateral benign gynecomastia at the left side and coincident symmetrical pectus excavatum deformity without cardiopulmonal restriction seeking for aesthetic improvement of both deformities. **e–f** Same patient 7 years after simultaneous mastectomy at the left side, using the same surgical incision for simultaneous silicone implantation at the central presternal region

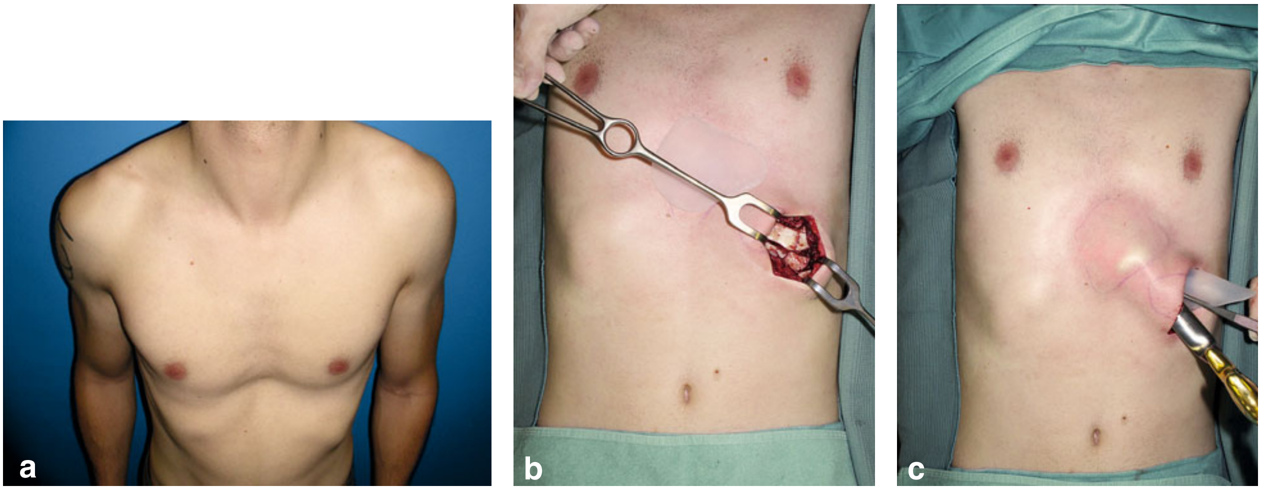

Fig. 6a. 31-Year-old male with minor asymmetrical pectus excavatum and unpleasing rib hump deformity at the left costal arch seeking correction of both deformities. **b** Same patient intraoperatively after completion of subperichondrial rib hump resection. **c** Same patient using the same surgical access for subcutaneous custom-made silicone implantation

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6.8 Vacuum bell procedure according to Eckart Klobe (nonsurgical)

Micha Bahr

6.8.1 Introduction

The conservative therapy of funnel chest deformities has a long tradition. Several of these treatments are described [3, 4], but most of them do not really improve the contour of the thoracic wall.

In 1992, the funnel chest patient Eckart Klobe, desired an improvement of his own deformity, but declined to undergo surgery and developed a special device, which he named vacuum bell, for the therapy of his pectus excavatum deformity. During a period of 2.5 years he was able to elevate his funnel with this self designed vacuum bell. This bell was built with silicone and plaster of paris, bought in a do-it-yourself-store and it was evacuated with a water jet pump (Fig. 1). After 30 months the thoracic wall was elevated to an extent that no funnel was visible any more.

After that success, based on a single own experience, he started to design a professional vacuum bell for a non-surgical funnel chest therapy. Since 2000 he searched for physicians, who wanted to gain experiences with this non-invasive method of deformity correction, but nobody was interested.

The idea to improve funnel chest deformities with negative pressure was not new. In the beginning of the 20th century Professor Hans Spitzy from Vienna and Professor Fritz Lange from Munich already intended to correct funnel chest deformities with so-called vacuum bells. They used a glass bell and could demonstrate that the funnel depression was elevated very quickly during the bell application, but as a drawback the skin was injured because the materials were not suitable for such kind of a therapeutic application [6].

Many patients with funnel chest deformities desire and literally seek for methods to improve the aesthetically annoying stain of their thoracic wall, but they are reluctant to undergo surgery because of the reported pain associated with postoperative recovery and the risk of imperfect results with remaining scars. In many cases of pectus excavatum the degree of pectus deformity does not immediately warrant surgery, however, patients more than ever request some kind of non-surgical treatment.

For these selected patients in 2002 we started to use the vacuum bell according to the inventor Eckart Klobe to improve the funnel chest deformity. With the following years more and more departments in Europe started to use the vacuum bell procedure, so that nowadays it has developed to a common non-surgical therapeutic alternative versus invasive surgery in specialized centers [1, 2, 5].

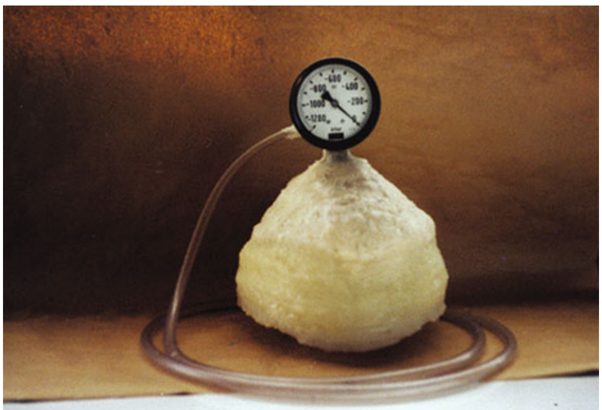

Fig. 1. The prototype of the vacuum bell

6.8.2 The vacuum bell according to Eckart Klobe

The body of the vacuum bell is made of a silicon ring and a transparent polycarbonate window. At the window an adapter for a simple suction bulb is fixed, designated to evacuate the air from the bell. The bell itself is produced and available in three sizes: “small” for children up to 8 years, “medium” for children up to 12 years, and “large” for children and adolescents elder than 12 years and adults. Since 2 years a vacuum bell for female patients with the shape of an eight is available. This shape provides with the facility to apply this kind of treatment in female patients even during and after full development of their breasts. The

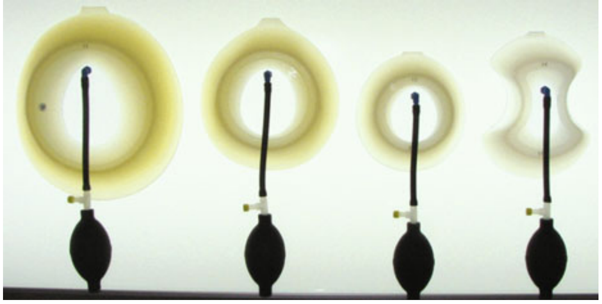

Fig. 2. Variants of the vacuum bell according to Eckart Klobe

vacuum bells of Eckart Klobe are certified, patent-registered, and are liable to the German medical standards (Fig. 2).

The vacuum bell works with two mechanisms. First, there is the negative pressure, which elevates the sternum toward the cavity of the bell. Second, to improve the contour of the deformed ribs, it is essential to apply some kind of pressure at the areas around the funnel or the bell cavity, which is the border of the funnel deformity. This pressure is produced by a silicon ring around the bell cavity, molded to the usually irregular surface of the thoracic wall. Both mechanisms provide with the contour that should be achieved to the thorax.

Before the development of the vacuum bell therapy it was hard to believe that it could be possible to elevate a sunken sternum with vacuum power alone. To prove evidence of this mechanism, CT scans of a thorax with funnel chest deformity were made, first without and then with the application of the vacuum bell. The time period between the situation without bell application and the second CT scan with evacuation took only 2 min. The second CT scan definitely showed that the sternum was elevated and the distance between the vertebral bodies and the sternum was elongated about 30% (Figs. 3 and 4).

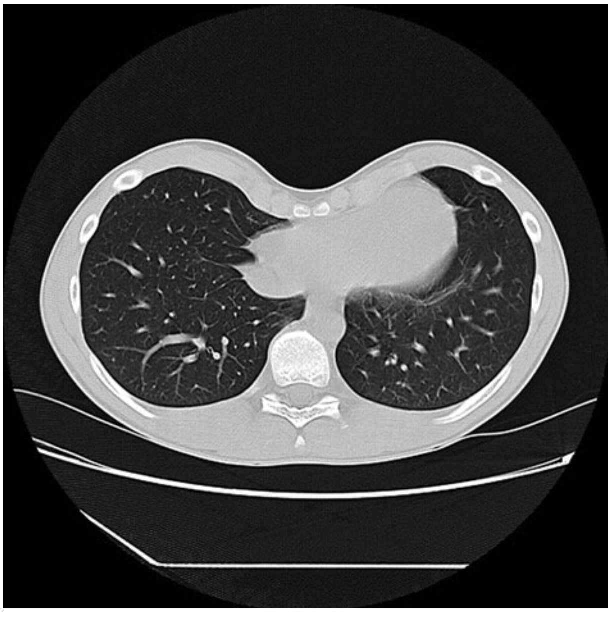

Fig. 3. CT scan of a funnel chest patient without vacuum bell

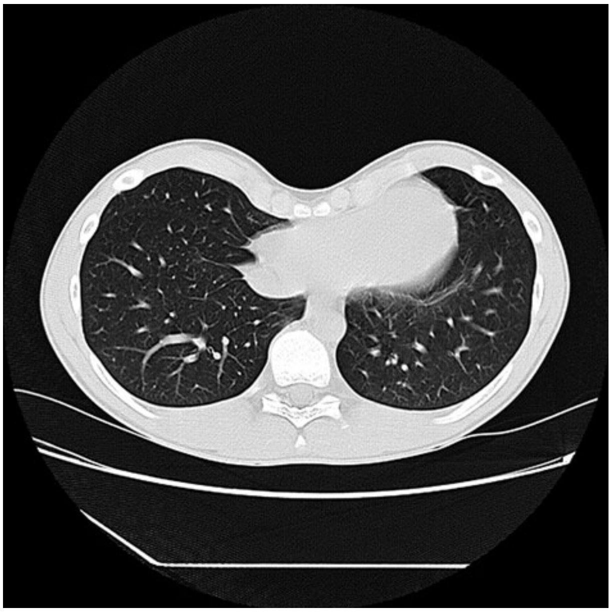

Fig. 4. CT scan of the same patient 2 min after evacuation of the vacuum bell

After this preliminary examination the further development and refinement of the vacuum bell treatment for improvement of funnel chest deformities started.

6.8.3 Vacuum bell procedure

All patients are informed that there exist different surgical options for funnel chest therapy, which could combine the requirements of aesthetic and functional remodeling of the thoracic wall. If patients decline an operation due to several or individual reasons, they are informed about the opportunity of a conservative therapy according to Eckart Klobe. They also are informed that this is a relatively new, however, not invasive kind of funnel chest therapy and that there are no long-term results available so far. If they still prefer this non-

Fig. 5. Application of the vacuum bell in the vertical position

surgical method, after standard clinical examination the optimal size of the vacuum bell is defined. The patients learn the proper application and utilization of the vacuum bell. First of all, it is important that the center of the polycarbonate window must be placed exactly above the bottom of the funnel. Usually the vacuum bell is applied in an upright position of the patient (Fig. 5). In patients with an asymmetric funnel chest deformity it could be useful also to apply the bell in a horizontal position. With the vacuum bell now being in position, the patients learn how to evacuate it. The patients are then equipped with the vacuum bell and start therapy at home for half an hour twice a day. After 1 month the patients present again as outpatients for consultation and discussion of potential problems with the current therapy. The position of the vacuum bell can be optimized and follow-up should take place now every 3 months.

It is suggested to start with a lower negative pressure during the first 3 months in order to allow the skin to adapt to the mechanical irritation caused by the foreign material that is applied with pressure and to relax the ligaments of the costal joints slowly. After that period the patients are requested to evacuate the bell with increasing power up to the maximum of vacuum, so that the skin under the polycarbonate window still shows sufficient blood circulation. After 3 months the patients should prolong the time of therapy up to 1 h, twice a day. The time of therapy should not exceed over 1 h twice a day because the skin due to the vacuum bell will suffer from this treatment irritation.

6.8.4 Patients

The vacuum bell treatment is feasible in patients of each group of age. The optimal age is between 9 and 18 years. In younger and smaller patients this treatment is applicable with the smallest bell designed for patients between the age of 5 and 8 years. The experience, however, shows that the treatment is not sufficiently effective in these small patients, because the skeletal structures of the anterior thoracic wall are still very pliable. As a consequence of this the funnel might sink back very fast into the initial position. It must be also discussed, whether such a therapy is useful in patients, who due to their youth do not yet care about the funnel chest deformity or as grown-ups do not mind about or suffer from their deformity. Especially these adolescent or adult patients might be stigmatized during the therapy and the formerly disregarded deformity becomes a psychological burden. Frequently parents wish this therapy for their children, because it represents an alternative to invasive surgery. It must be recognized, however, that also this vacuum bell therapy could be a painful and time-consuming treatment.

It is very important to ask the patients for their desires and expectations concerning this kind of therapy. If they doubt to have sufficient motivation to undergo such a therapy for up to or over 2 years, the vacuum bell treatment should not be suggested or performed. In some cases it could be useful, to test the vacuum bell treatment for 1 month, then interview the patient and reevaluate his motivation. For the case that ongoing compliance and motivation are absent or doubted for the vacuum bell treatment, it might be meaningful to discuss the variant of an operation.

The vacuum treatment is also feasible in older patients, but because of the increasing skeletal rigidity with age it requires more time to elevate the thoracic wall depression to acceptable almost normal condition and shape. During the last 6 years many patients of each age group underwent vacuum bell therapy for funnel chest deformity correction. All of these patients were very well motivated and compliant. The time of therapy averaged 30 months. After 1 month body posture improved markedly and the sternum depression could be elevated by 1 cm in all patients immediately after the vacuum bell application. After 3 months in 50% of the patients the elevation of the sunken sternum to a normal level

Fig. 6. Funnel chest patient before vacuum bell treatment and after 5 months of therapy

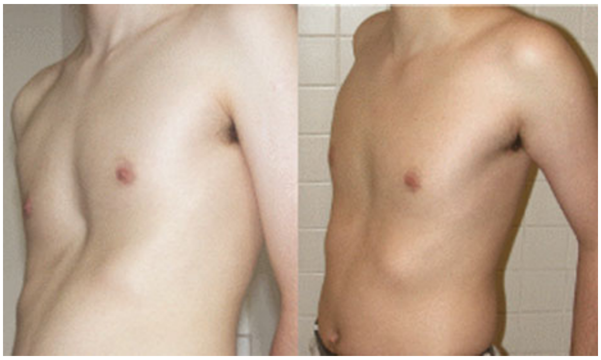

Fig. 7. Another funnel chest patient before vacuum bell treatment and after 5 months of therapy

lasted for 30 min up to 2 h, subsequent to daily therapy. During the following months an increasing consolidation of this status of elevation was obtained. Many of these patients complete therapy between 24 and 30 months because of achievement of a sufficiently aesthetic improvement and all of them were very satisfied with the results obtained (Figs. 6 and 7).

6.8.5 Complications

Complications in this therapy are very rare and harmless. There remains no permanent skin discoloration or discomfort. During initial treatment all patients experience moderate pain at the sternum and 53% of the patients report pain at the costovertebral joints. The pain, however, is very moderate, not requiring analgesic medication in any patient so far. One patient in our series suffered from unaccountable transient paresthesia in the right arm and leg during the first applications of the vacuum bell. Three patients experienced orthostatic disturbances during the first application of the vacuum bell, but this did not recur in subsequent procedures. In one patient we noticed dilatation of some skin vessels after 15 months of vacuum bell therapy. No other complications were observed.

6.8.6 Intraoperative use of the vacuum bell

The most difficult part of the minimally invasive repair of pectus excavatum (MIRPE after Donald Nuss) during insertion of the introducer and ensuing metal bar is to cross the space between the sternum and the pericardium to reach the other side of the thorax. This is because the space between sternum and pericardium is very narrowed in patients with a pectus excavatum deformity. Therefore it appears reasonable to reduce the risk of organ damage by enlargement of the retrosternal space using a tool to increase the safety of placing introducer and pectus-bar into the thoracic cavity. Some surgeons perform this intraoperative elevation using a bone hook through an extra skin incision at the sternum. To avoid such undesired incisions and resulting, occasionally hypertrophic or unsightly scars, it seems more useful to elevate the sternum or the anterior thoracic wall by non-invasive vacuum power.
During the Nuss procedure a medium-sized sterile vacuum bell is placed in such a way that the center of the window is placed right above the bottom of the funnel. The first steps of the Nuss procedure are performed in a standard way as described in Chapter 5.3.1.1. After preparation of the bilateral thoracic access for the ensuing intrathoracal part of the operation, the vacuum bell is placed exactly and evacuated under thoracoscopic view and the part of the anterior thoracic wall encompassing the sunken part is lifted. As long as the sternum is elevated, the placement of the introducer and the pectus-bar is much easier and with minimized danger of organ damage. It takes only 2 min to elevate the sternum, but it saves much more time with an easier and more secure placement of the hardware and with much better survey over the manipulation maneuvers within the thoracic cavity. Furthermore, based on this indirect rapid expansion of the thoracic cavity the thorax is preformed and the placement of the pectus-bar is much less traumatizing to thoracic wall structures in contrast to the conventional Nuss procedure (Figs. 8–10). This latter condition may be more the case for adult patients with a more rigid thoracic cage than for children.

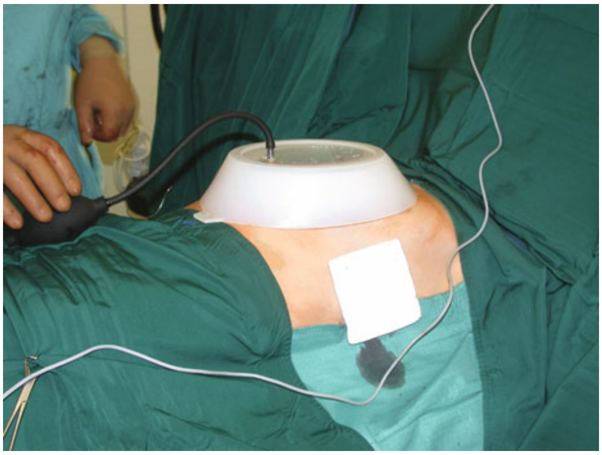

Fig. 8. Intraoperative application of the vacuum bell

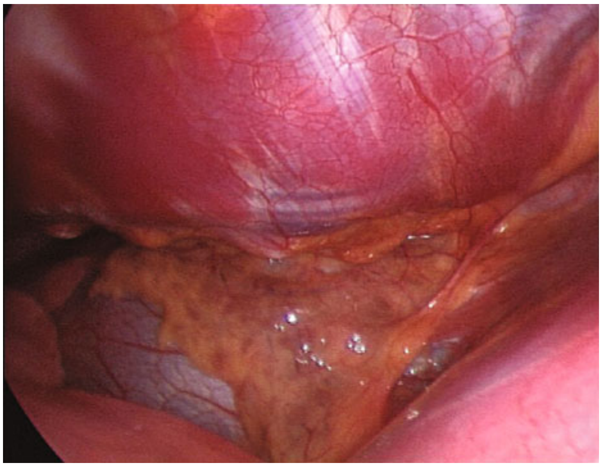

Fig. 9. Thoracoscopic view to the substernal space without the vacuum bell

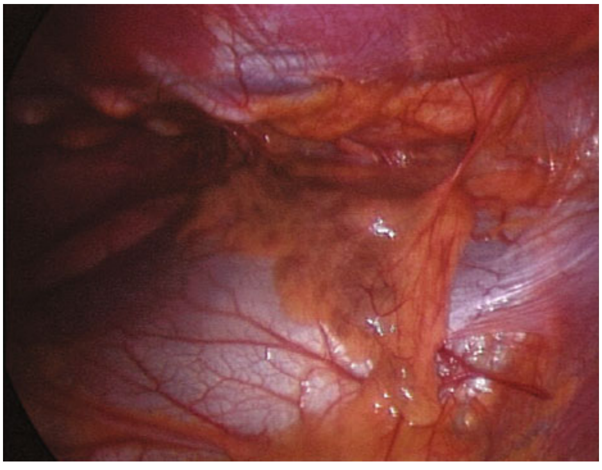

Fig. 10. Thoracoscopic view to the substernal space with evacuated vacuum bell

6.8.7 Preoperative use of the vacuum bell

There is an ongoing discussion whether to use the vacuum bell preoperatively prior to a Nuss procedure or not. It may become apparent that this kind of “pre-expansion” represents a helpful adjuvant pre-treatment for very deep funnel chest deformities. Especially in such patients, and because of the pre-lift of the sternum for several months preoperatively, the risks and pitfalls inherent within the Nuss procedure are reduced. The period of preoperative vacuum bell therapy depends on the deepness of the funnel bottom. Another discussion about preoperative vacuum bell therapy relates to the preoperative improvement of the body posture and the relaxation of the costal joint ligaments as well as intrathoracal muscles adherent to the sternum. This “pre-expansion” also seems to be advantageous to lower pain after the NUSS procedure, because this “pre-expansion” process loosens all anatomical structures withstanding the pressure of the pectus-bar.

6.8.8 Conclusion

The vacuum bell treatment according to Eckart Klobe seems to be a promising alternative for patients who decline surgical correction, for aesthetic indication as well as for functional improvement of impaired fitness. It also shows benefits in the pre-treatment of extensive deformities in order to facilitate the surgical access itself and thereby might also alleviate postoperative pain. However, there are still no long-term studies published and the reports on the application of the vacuum bell are small series with patient groups up to 100 patients so far, but the promising preliminary experiences raise expectations for further application and development.

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6.9 Pectus-bar removal technique

Anton H. Schwabegger

The technique of bar removal is shortly described already in Chapter 6.3 (Kuhn and Nuss) but herewith we intend to address some particular hints and technical requirements for at times intricate removal of the bar especially in the adolescent and adult patient, and furthermore if they have been left in place inadvertently for several years more than scheduled.

The type of anesthesia and the positioning of the patient do not deviate from the descriptions of Kuhn in Chapter 6.3 and ours in Chapter 5.2. The provision of current chest X-rays appears especially important for an appropriate localization of the metal parts. Such imaging is the more important, the more obese a patient presents, because herewith the pectus-bar wings and occasionally implanted stabilizers can hardly be found just by palpation underneath adipose and muscle tissue layers.

However, particular problems arise in removal of pectus-bars in adults, because the anatomy and shape of the thorax thus also the shape of the implanted pectus-bar present different and rigidity of the skeletal structures with different biological reactions, e.g., formation of callus, may complicate their removal. After duration of 3 years, the pectus-bar wings may also be dislocated to dorsal and thus the skin incisions along pre-existing scars from implantation must then be elongated further

Fig. 1. Incision at the left thoracal side, the end of the pectus-bar is hooked up with the flipper instrument, usually used to twist the pectus-bar during implantation. The pectus-bar wing is unbent with the flipper prior to extraction, in order to circumvent lesions of lungs and heart during extraction

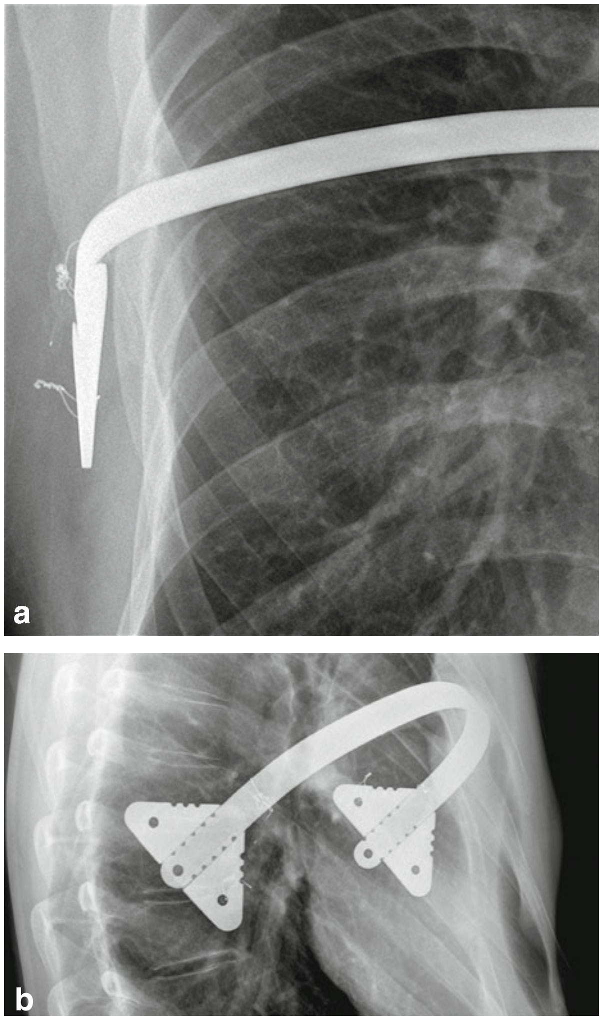

Fig. 2a. Right wing of a pectus-bar with attached triangular stabilisator, in a frontal X-ray aspect. Notice the broken fixation wires, potentially caused by dislocation of the pectus-bar wing and its stabilisator from the ribs. **b** Same situation in a lateral X-ray aspect. The twisting of the pectus-bar to cranially is clearly visible now, making the disruption of the wires understandable

to dorsal. This extension of the incisions may be necessary in order to mobilize the dislocated metal bar wings to that extent that it can be hooked to the pectus-bar flipper (Fig. 1).

In former cases however occasionally used but through dynamic respiration forces usually broken and therefore mostly dislocated fixation wires can be localized by means of the X-ray pictures prior to surgical incision (Fig. 2a, b).

In the case of major tipping of the pectus-bar it can at times become necessary to place the skin incisions, which serve for hardware explantation, remote from the pre-existing scars.

Occasionally used stabilizer plates must be shifted to dorsal in order to remove them from the bar wings prior to the pectus-bar explantation itself. This may be feasible only through extensive mobilization of the tissue embedding the bar wings and the adjoining part of bar strut, which wears the stabilizer. Herewith a sufficiently ample tissue pocket must be dissected and the adjacent, usually scarred musculature be mobilized to create sufficient place for the maneuver of mobilization of the stabilizer. A further problem arises in the use of triangular stabilizers, which for the positioning of the pectus-bar were promised to provide with more stability against the sequels of twisting. Then during scheduled explantation after years these triangular devices require much more ways to dorsal into the tissue for taking them off, which is up to two cm of space needed (Fig. 3a, b).

Removal of these stabilizers prior to pectus-bar removal is necessary to create sufficient space to place the flipper or similar tools to enable proper positioning for unbending the strut wings. Especially in the cases of adults, in which ongoing forced pressure, caused by the functional-anatomical factors (Chapter 2.1) weighing on the pectus-bar for several years, the bar wings are shifted further dorsally in many cases (Chapter 12.1). The originally set scars, however ideally placed for the access of hardware implantation, then no longer suffice for adequate mobilization of the stabilizers and bar wings, thus must be extended or placed further dorsally.

Furthermore if formation of callus embedding the bar wings and stabilisators occurred after several years, positioning of the flipper instrument for bar unbending is cumbersome through a desired small still aesthetically pleasant incision (Fig. 4).

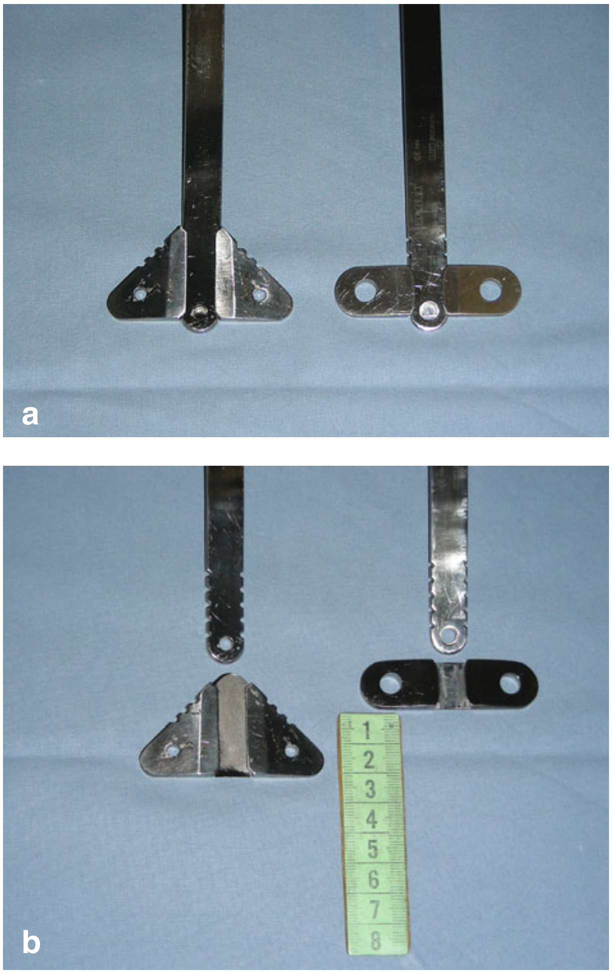

Fig. 3a. Triangular and strap-shaped stabilisators attached to pectus-bars to depict their size. **b** During explantation and detachment of the stabilisators this depiction gives evidence that the triangular stabilisator necessitates about 2 cm more range of posterior shifting along the strut to be shoven off

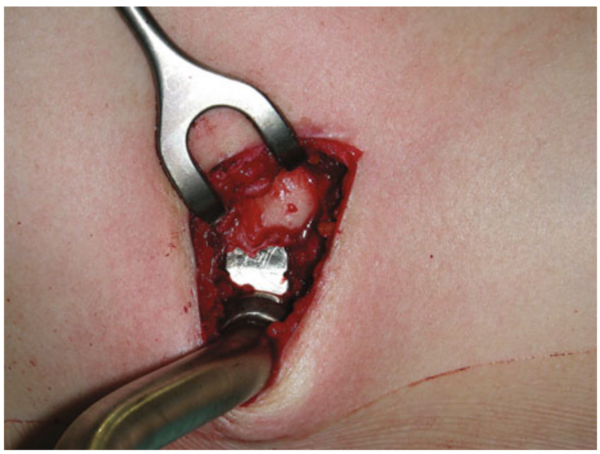

Fig. 4. A desired short skin incision may be of disadvantage, if bony callus formation cuffs the pectus-bar, which renders positioning of the flipper instrument for the purpose of unbending the wing of the strut difficult

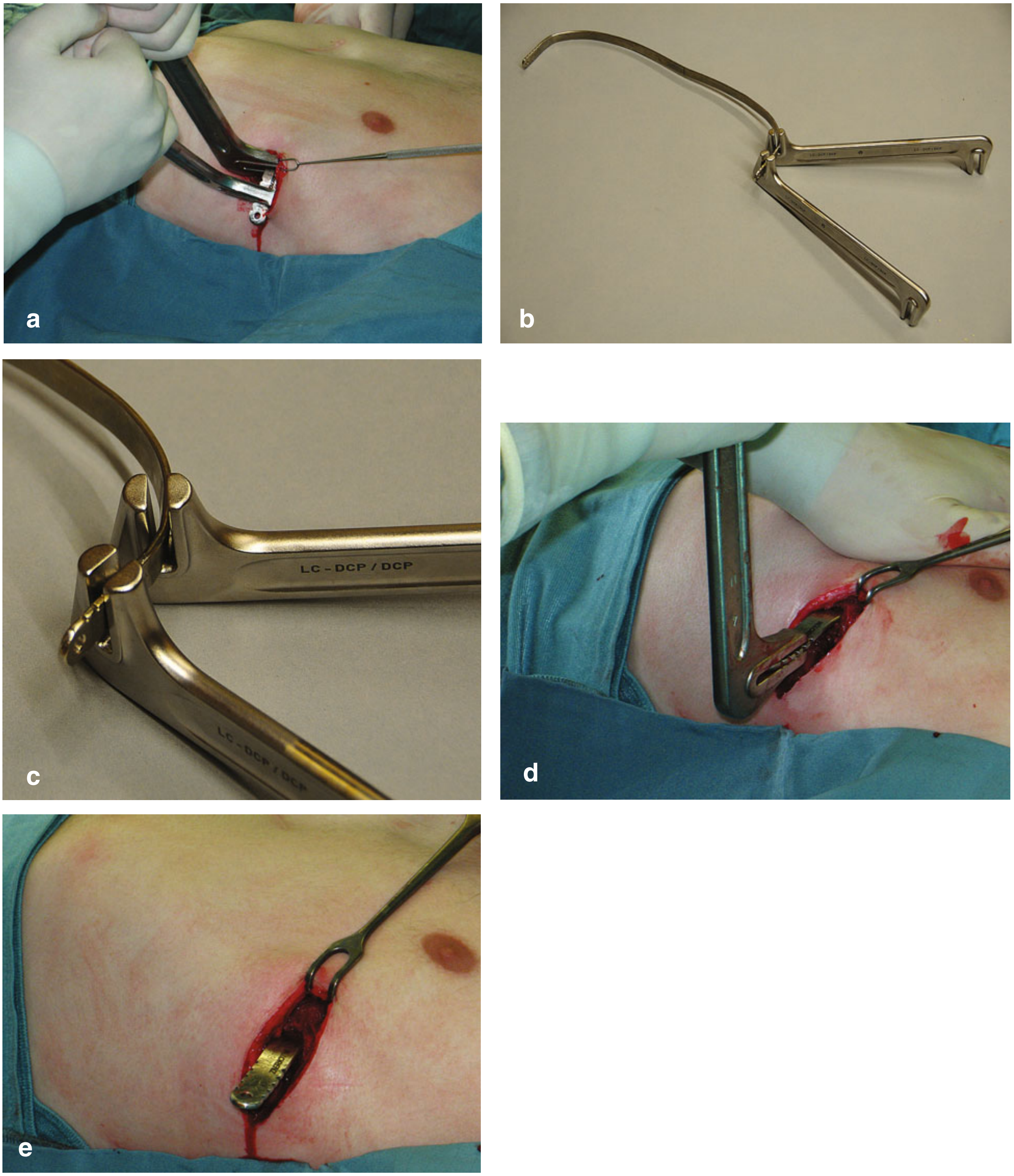

Fig. 5a. Wrench irons set in place to easily unbend the left wing of a pectus-bar into a horizontal plane, in order to enable extraction from the right side. **b** Wrench irons placed at a pectus-bar demonstrate the ideal site of application for proper unbending in order to circumvent rib fractures. **c** Close-up view to show the ample jaws of the wrenches that may be advantageous in cases, where the wings of a pectus-bar are already curved or damaged to such an extent, that the slot of the flipper instrument usually well fitting to the bar wing may not be attached any more. **d** The wrench at its second end is constructed with jaws wider than the other one, which are able to embody even a distorted wing of a pectus-bar for adequate unbending. **e** Pectus-bar wing bent into a horizontal plane, ready for securing extraction from the other (right) side. Sterile gel applied to this end may alleviate the transthoracal extraction

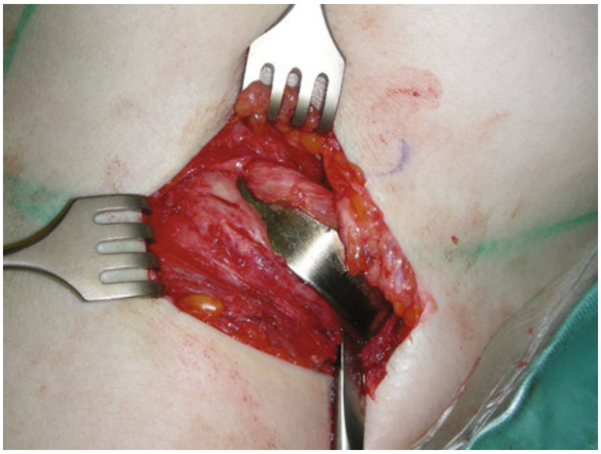

Fig. 6. Chisel needed to liberate pectus-bar embedded in bony callus formation

In such cases, when the flipper instrument cannot hook up the bar wings, wrench irons, usually used in osteosynthetic trauma surgery, may be helpful to lift up and simultaneously bend the bar wing to a desired position (Fig. 5a–e).

Prior to bending up the bar wings, which in some cases are embedded by bony callus tissue, such excess of bone must be removed using sharp chisels (Fig. 6), in order to avoid rib fractures resulting from undue bending forces. Anyhow, if such callus is present, it should be removed entirely, because after pectus-bar removal such callus remnants may generate new callus due to the irritation of surgical manipulation and may cause complaints such as tenderness on pressure, visibility and even aesthetically eye-catching humps in slim patients. Occasionally during growth spurts and through respiration movements friction between the pectus-bar and the bony part of the rib develop because of increasing tight contact. Thus bony erosions (Fig. 7) and weak zones at the rib exist, which might result into a painful fracture, if inappropriate forces are applied during pectus-bar explantation. In order to avoid such complications it is a prerequisite to have actual X-rays of the chest present prior to perform explantation surgery.

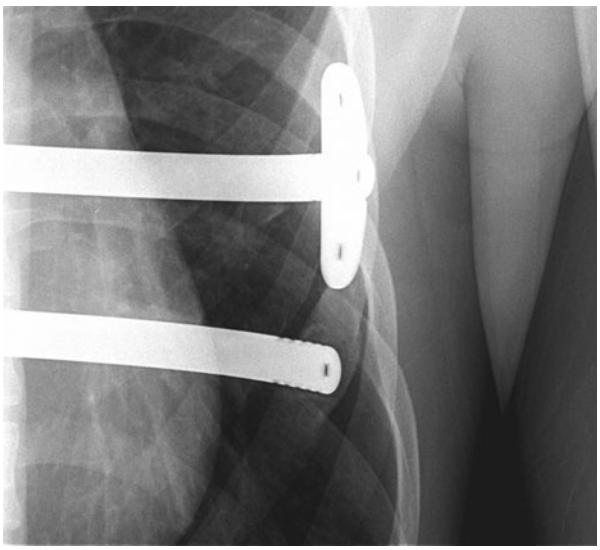

Fig. 7. Erosion of bone at the wing's end of the lower pectus-bar caused by ongoing friction and pressure due to growth spurt and permanent respiration movements

It appears very meaningful, that already during the pectus-bar implantation on the one hand the size of the pectus-bar is selected not too long, and that the skin incision is not set too far ventrally on the other hand. However, nowadays we do not find the utilization of laterally placed stabilizers very useful, as the wings of the pectus-bar can be sufficiently fixed to the ribs using absorbable strong sutures and because of other distinct reasons [1], which are described in Chapter 6.4.

At our institution, because of the prevalence of adolescents and adults to be operated, the pectus-bar explantation is carried out exclusively in supine position. Some authors sometimes describe it to be performed in lateral decubitus position. This maneuver only then succeeds without danger, as long as the tips of the metal strut are only slightly bent up and removal along the radius of the arch of the pectus-bar as well as of the chest is feasible. That is only the case, if the pectus-bar lies in situ almost perfectly round-arched. However, such an arched form of the pectus-bar almost exclusively only in children and therein very elastic thoracic cages is

Fig. 8. Comparison of two shapes of the pectus-bar used at different ages. The right (upper) one is shaped like a wave or "M" and is used frequently in adolescents and adults with a matured shape of the chest. The left (lower) and smaller one is almost curvilinear round and formed for implantation in children with yet pliable skeletal structures

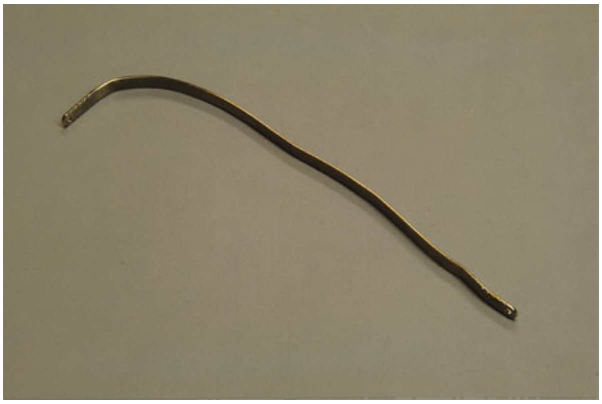

Fig. 9. Pectus-bar extracted from an adult patient, showing one wing untreated, while the other wing that passed through the chest cavity is bent up to a horizontal plane to avoid any intrathoracal injuries

used (Fig. 8). Upon hardware extraction then the thoracic wall may follow the shape of the pectus-bar due to its elasticity without any problems, but it will not behave like that in elder patients with a rigid chest. In adolescent or adult patients, this round-arched shape of a pectus-bar never comes into consideration, because at that age the transversal diameters and the anterior thoracic wall are almost always shaped like a horizontal "8" thus the implantation of a round-arched strut would be impossible or in danger to twist or dislocate because of undue pressure. On the basis of this substantially different overall shape of the thorax, a differentially formed pectus-bar is required to lift up a sunken sternum and the adjacent ribs. The metal strut in these cases is formed like an undulatory "M" (Fig. 8), thus in contrast to children may not be extracted along a simple curvilinear round arch in lateral decubitus position. Intentional round extraction without bending the distal end will definitely hook up inner organs with resulting fatal consequences. Prior to extraction, one end must be unbent almost flatly into a horizontal plane (Figs. 5e and 9) in order to avoid such injury to the intrathoracal organs (Chapter 6.3).

On the basis of capsule development around every implanted foreign material, a rigid scar will also cover the pectus-bar even intrathoracally after months and years. That is why especially in adult patients the pectus-bar seems to be trapped by that scar tissue, which renders extraction of long struts rather difficult. It may be helpful in these cases, to hook up two bar flippers at the strut, each at one side of the unbent wing. Then along the axis of the straightened bar rotation is applied with force to loosen the intrathoracal capsule.

In children with a short length of the pectus-bar this is of fewer importance, but is necessary in adults with very long struts, especially if the bar stayed in situ for several years and is shaped with multiple arches. The distal and bent wing of the pectus-bar is moistened with sterile gel to alleviate its extraction and to circumvent any traction forces of the interdigitations at the bar's wing within the intrathoracal scar-capsule.

After explantation the patients are followed-up for another year to observe the further course, taking photos and measurements with thorax calipers.

Reference

[1] Watanabe A, Watanabe T, Obama T, Ohsawa H, Mawatari T, Ichimiya Y, Abe T (2003) The use of a lateral stabilizer increases the incidence of wound trouble following the Nuss procedure. Ann Thorac Surg 77:296–300