ORIGINAL ARTICLE

Simplified open repair for anterior chest wall deformities. Analysis of results in 205 patients

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Pectus arcuatum;
Sternochondroplasty;
Ravitch-type repair

Summary

Introduction: Pectus deformities are the most frequently seen congenital thoracic wall anomalies. The cause of these conditions is thought to be abnormal elongation of the rib cartilages. We here report our clinical experience and the results of a sternochondroplasty procedure based on the subperichondrial resection of the elongated cartilages.

Hypothesis: This technique is a valuable surgical strategy to treat the wide variety of pectus deformities.

Patients and methods: During the period from October 2001 through September 2009, 205 adult patients (171 men and 34 women) underwent pectus excavatum (181), carinatum (19) or arcuatum (5) repair. The patients’ pre and postoperative data were collected using a computerized database, and the results were assessed with a minimum 2-year follow-up.

Results: The postoperative morbidity rate was minimal and the mortality was nil. The surgeon graded cosmetic results as excellent (72.5%), good (25%) or fair (2.5%), while patients reported better results. Patients with pectus excavatum were found to have much more patent foramen ovale (PFO) than the normal adult population, which occluded after the procedure in 61% of patients, and significant improvement was found in exercise cardiopulmonary function and exercise tolerance at the 1-year follow-up.

Discussion: Our sternochondroplasty technique based on the subperichondrial resection of the elongated cartilages allows satisfactory repair of both pectus excavatum and sternum prominence. It is a safe procedure that might improve the effectiveness of surgical therapy in patients with pectus deformities.

Level of evidence: Level IV. Retrospective study.

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Introduction

Pectus deformities affect the chest wall in two ways: the concave deformities, pectus excavatum, or funnel chest (the most frequent), and protruding deformities, pectus carinatum and pectus arcuatum, or pouter pigeon breast (the rarest). The anterior or posterior displacement and deformation of the sternum result from the elongation of the rib cartilages, present at birth or developing during the adolescent growth spurt. Robicsek et al. [1] emphasized this mechanism and considered that pectus deformity treatment involved the correction of this axial overgrowth. Our sternochondroplasty technique, based on the subperichondrial resection of elongated cartilages, meets this objective perfectly [2]. This study aimed at assessing the anatomical, cosmetic, and cardiopulmonary function results of this technique.

Patients and methods

Almost all patients referred for evaluation of chest wall deformity were already informed of the surgical techniques from informative pectus Web sites and had generally chosen to undergo our sternochondroplasty technique. Except for particular cases (Marfan syndrome), the intervention was considered for patients at the end of the adolescent growth spurt and with no upper age limit. If the patients did not have the required age (15 years for girls and 17 years for boys), they underwent annual follow-up and more recently, for seven of them with pectus excavatum, orthopaedic management with a “vacuum bell” [3]. Complementary information was provided, notably on the functional benefits to expect from the surgery. The examination assessed the severity of the deformity, with the criterion of sternal depression depth exceeding 25 mm for pectus excavatum. Protrusion of the lowermost costal cartilage or depression along the lower border of the thorax —Harrison groove— (on one or both sides) and, in females, distortion and/or mammary hypotrophy (usually on the right side) were noted. Vertebral column abnormalities and signs of Marfan syndrome were systematically sought.

At the end of the examination, the chest wall deformity was classified according to the cartilage involvement and the presence or absence of an asymmetry [2]:

- 3rd to 7th rib cartilages: standard forms of pectus excavatum and pectus carinatum;
- 2nd to 7th: “extensive” forms of pectus excavatum and pectus carinatum; pectus arcuatum involved with a lower depression (rare);
- 4th to 7th: “low” forms of pectus excavatum or pectus carinatum;
- 2nd to 4th or 5th: “high” forms, pectus arcuatum.

Preoperative assessment

The morphological assessment included thoracic X-rays and a chest computed-tomography imaging study. Calculation of the “pectus index” (Haller Index) was used to grade severity of the deformity and was compared to the “theoretical pectus index” (corresponding to the thoracic morphology of an identical healthy human) [4] (Fig. 1a). The sternum and the manubriosternal angulation were studied on sagittal slices, and the morphology of the rib cage was studied on 3D reconstructions. These constants were also used to calculate the “postoperative pectus index” (Fig. 1b) and assess cartilage regeneration (Fig. 2). Comparison of the “theoretical pectus index” and the “postoperative pectus index” provided objective evaluation of the results [4].

The functional cardiopulmonary assessment for patients with pectus excavatum included lung function tests at rest, followed by cardiopulmonary exercise test on a cycle ergometer, the results of which were collected on 70 patients enrolled in a prospective study, which took place from December 2005 to May 2009. Since December 2005, transthoracic echocardiography was routinely performed. To assess a patent foramen ovale (PFO), all patients underwent a microbubble test [5]. For comparison purposes, these investigations were renewed at specific times after the procedure: the echocardiography at 6 months and the lung
Simplified open repair for anterior chest wall deformities

Figure 2  Postoperative 3D chest CT scans after treatment of a low form of pectus excavatum, showing the neocartilages with osseous metaplasia.

function tests including exercise testing 1 year after the surgery.

Sternochondroplasty surgical technique

Sternochondroplasty was performed through a limited transversal incision or a submammary incision in female patients. The chondrosternal wall was exposed by minimal detachment of the pectoralis major muscles, then the rectus abdominis muscles, sparing the posterior part of the sheath. The subperichondrial resection was complete from the 3rd to the 6th rib cartilages and limited to the extremity of the 7th in the standard forms. In the extensive forms, this was completed by a subtotal vertical section of extremities of the 2nd rib cartilages. In the “low” forms, the subperichondrial resection extended from the 4th to the 6th rib cartilages and was limited to the extremity of the 7th. Finally, in the “high” forms, the resection involved the 2nd, 3rd, and 4th (or 5th) rib cartilages. A wedge transverse osteotomy of the upper sternum, followed by a gentle fracture of the posterior table, allowed elevation of the distal sternum (pectus excavatum: Fig. 3a) or push-down in a proper position (pectus carinatum), associated with twisting in asymmetrical forms. In June 2008, the transverse sternum osteotomy became optional, most particularly in the case of extensive pectus excavatum, so as not to worsen the manubriosternal angulation defect characteristic of this form, as well as in moderate case of pectus carinatum.

In pectus excavatum, chest wall stability was ensured by an easily removable retrosternal metallic strut (Medicalex®, Bagneux, France), placed anterior to the ribs laterally and secured to the base of sternum with an absorbable suture (PDS II 1, Ethicon France, Issy les Moulineaux, France). The extremities of the 7th rib cartilages were stitched to the base of the sternum or to the xiphoid process. The perichondrial sheaths were sutured continuously using an absorbable running suture (Optime 1, Péters Surgical, Bobigny, France), providing tension for the adjacent intercostal spaces (Fig. 3b).

In the case of diastasis, the pectoralis major muscles were sutured along the midline. After reinsertion of the anterior part of the sheath of rectus abdominis at the lower edge of the sternum, the pectoralis major and rectus abdominis muscles were reaproximated, by suturing their respective sheaths. Submuscular drainage was ensured, using two suction drains (Blake n° 10; Ethicon France, Issy les Moulineaux, France).

Figure 3  Pectus excavatum: a: diagram showing the subperichondrial resection of the rib cartilages and the transverse wedge osteotomy of the anterior table of the sternum; b: aspect after suture of the cartilage sheaths and stabilization of the chest wall with a metal splint.
Patients

During the period from October 2001 through September 2009, 205 adult patients (171 men and 34 women) with a mean age of 25 ± 14 years underwent pectus deformity repair. There were 181 patients with pectus excavatum (88.3%), 19 with pectus carinatum (9.2%) and five with pectus arcuatum (2.5%). In 12 patients the pectus deformity was associated with a Harrison groove. Last, in two patients the pectus arcuatum was associated with a lower depresion.

Three patients presented with recurrence after treatment of pectus excavatum in another institution. Of the six patients with Marfan syndrome, two (a 14-year-old and a 37-year-old) underwent a staged repair of pectus excavatum, combined with repair of an aortic aneurysm under cardiopulmonary by-pass [6]; another 63-year-old female patient with no Marfan syndrome underwent the same combined procedure.

Additional procedures were performed: bilateral (n = 10) or unilateral (n = 8) tangential resection of protruding lowermost cartilage; straightening or curved costal arches, by wedge osteotomy and gentle fracture of the posterior cortex in the case of pectus excavatum (n = 15); correction of moderate sternum asymmetry or manubriosternal protrusion (pectus arcuatum), by tangential resection of the anterior table of the sternum (n = 55).

Peri- and postoperative patient management

Perioperative cefamandole antibiotic prophylaxis (1.5 g) was administered. Postoperatively anticoagulant was not given, and analgesia was provided with paracetamol, a nonsteroidal anti-inflammatory drug and intravenous opioid analgesics through a patient-controlled infusion pump, or epidural analgesia.

The patients were allowed to stand up on day 1 after the procedure. This was facilitated by the efficient chest wall stabilization, which prevented the flail chest phenomenon. The suction drains were removed on day 2 or day 3, and the patients were discharged between the 3rd and 5th day. In the case of pectus excavatum, the metallic strut was removed through a 1 cm long lateral incision, under local anesthesia on an outpatient basis, 6 months after the initial procedure.

The patients were systematically followed-up (after metallic strut removal in the case of pectus excavatum) to evaluate the results with a minimum follow-up of 2 years. In 19 patients, additional plastic surgery was required to improve the cosmetic result: scar revision (n = 9), associated in three cases with resection of an additional cartilage segment; lipofilling of a residual depression (n = 5), correction of bilateral (n = 3) or unilateral (n = 2) mammary hypoplasia with implant, and reduction mammoplasty (n = 1).

Data collection and evaluation of the results

The pre-, intra-, and postoperative patient data were prospectively collected in a database (Microsoft Excel), notably the results of the functional tests, which were collected in 70 patients enrolled in a study that was conducted from December 2005 to May 2009 [7]. This database included:

- personal data and medical history (Marfan syndrome, heart surgery), the type of chest wall deformity, the preand postoperative pectus index;
- the date of surgery, its modalities (scar length and additional complementary procedures), and its duration; intraoperative blood loss;
- the duration of postoperative hospitalization and any complications;
- later, any additional procedures and the duration of follow-up;
- the pre- and postoperative cardiopulmonary function test results;
- the cosmetic result as assessed by the surgeon compared to the patient’s self-assessment.

The cosmetic result was objectively evaluated as follows:

- excellent: normal chest morphology (Figs. 4 and 5);
- good: slight residual depression or curvature of the lower sternum; hypertrophic or keloid scar;
- fair: residual depression, with nevertheless more than 50% improvement compared to the initial presentation;
- failure: complete recurrence.

Statistical analysis

The statistical analysis was carried out using SAS software (SAS v8, SAS Institute Inc., Cary, NC).

The qualitative variables were described with their numbers and the proportions of their classes, the quantitative variables with the mean ± standard deviation. The surgeons’ evaluations of the results were compared with the patients’ evaluations using a Bhapkar test, a generalized McNemar test.

For the cardiopulmonary function results (pectus excavatum), the means of each variable were compared between the groups using a Student t-test for matched values, after verification that the values followed a Gaussian distribution. A value of P < 0.05 was required to confirm a difference between groups [7].

Results

Immediate results

Other than the six pectus repairs combined with aortic surgery, performed through a vertical median approach, the incision measured 13 ± 1.8 cm; intraoperative blood loss was evaluated at 114 ± 80 mL; the mean duration repair was 196 ± 51 min and postoperative hospitalization lasted 4.36 ± 1.36 days. None of the patients received a blood transfusion.
Postoperative complications

Early complications occurred in 17 patients (8.3%), 12 of whom treated on an outpatient basis:

- delayed wound healing due to prolonged lymphorrhea (6) or sepsis (2);
- chest wall hematoma treated by puncture (1) or evacuation (1);
- pneumothorax requiring a chest tube (1) and serous pleural effusion treated by puncture (2);

- pneumopathy (2) and atelectasia (1) in smokers, with a favorable outcome with antibiotics or after fiberoptic bronchoscopy;
- pulmonary embolism (1) occurring in the 3rd week, which resolved under anticoagulant treatment on an outpatient basis.

Late complications occurred in three patients (1.5%): untimely displacement of the metallic strut, repositioned twice through an elective lateral incision.

The most worrying complication was seen in a patient who had been operated 30 years before for pectus excavatum in another institution, in whom a forgotten foreign
body was discovered (during the sternochondroplasty for complete recurrence of the deformity), causing chronic sternal osteitis. This required serial revisions, leaving a residual depression as a sequela.

**Anatomic and cosmetic results**

One patient operated for pectus arcuatum, with an excellent immediate result, was lost to follow-up. Consequently, the analysis was conducted on 204 patients with a minimum follow-up of 2 years and a maximum of 8 years. From an anatomical point of view, the mammary distortions were corrected by the anterior chest wall reconstruction. In two patients, sternochondroplasty corrected an extrinsic bronchial compression due to pectus excavatum of the bronchus intermedius (responsible for a ventilation disorder), and of the middle lobe bronchus, which had been causing recurring pneumopathies. Finally, reconstitution of neocartilages with osseous metaplasia ensured chest wall stability and satisfactory long-term results (Fig. 2).

The surgeon evaluated the results as follows:

- excellent: 148 (72.5%);
- good: 51 (25%);
- fair: 5 (2.5%).

None of the patients experienced complete recurrence. Remarkably, the patients’ self-evaluation of the results was even more favorable (Bhapkar test: \( P < 0.0001 \)):

- excellent: 176 (86.3%);
- good: 26 (12.7%);
- fair: 2 (1%), with one drug-addict patient presenting invalidating residual pain.

The "theoretical pectus index" was compared with the "postoperative pectus index" [4] for 177 patients who had had both pre- and postoperative chest CT scans. This was an objective evaluation of the quality of the results (Table 1).

**Cardiopulmonary functional results (pectus excavatum)**

Of the 160 patients who underwent echocardiography exploration, 28 (17.5%) had a PFO that occluded in 17 cases after the intervention (61% of the cases).

The preoperative lung function tests at rest were within the lower limits of the theoretical normal values (90–95%) for the forced expiratory volume in 1 s (FEV1), forced vital capacity (FVC), and total lung volume (TLV); the surgical treatment did not improve these parameters. On the other hand, the preoperative cardiopulmonary exercise testing, which objectively assessed limitation in aerobic capacity (VO2 max: 35 ± 7 mL/kg per minute, 77 ± 2% of the predicted value), showed statistically significant improvement 1 year after surgery (38 ± 7 mL/kg per minute 87 ± 2% of the predicted value, \( P < 0.0005 \)). VO2 max increased with no modification in the ventilation reserve and the ventilation mode associated with normalization of the Q1 pulse (13.2 ± 3.1 vs. 14.8 ± 3.2 mL/beat, \( P < 0.003 \)), suggestive of better cardiovascular adaptation in exercise after surgery [7].

**Discussion**

The optimal period to undertake chest wall deformity repair, as well as the opportunity to perform surgery, and the therapeutic modalities are discussed. Historically, Ravitch was the pioneer of the modern treatment of these deformities, correcting pectus excavatum by resection of the elongated cartilages [8]. Significant improvement was introduced by Baronofski [9], preserving the perichondrium during resection of the rib cartilages, which ensured their regeneration and consolidation of the chest wall in a proper position. The therapeutic armamentarium was enhanced with both the Nuss technique, which consisted in placing one or two convex intrathoracic metallic bars that raise the chondrosternal wall by internal compression [10], and filling technique of the pectus excavatum with a silicone implant in a submuscular position [11]. Finally, orthopedic treatments have recently been developed: reduction of pectus excavatum

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**Table 1** Mean preoperative, theoretical, and postoperative pectus index calculated for 177 patients.

<table>
<thead>
<tr>
<th>Pectus Index</th>
<th>Pectus excavatum</th>
<th>Protruding deformities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preoperative (Haller)</td>
<td>4.03 ± 1.41</td>
<td>1.98 ± 0.46</td>
</tr>
<tr>
<td>Theoretical (preoperative)</td>
<td>2.45 ± 0.42</td>
<td>2.34 ± 0.56</td>
</tr>
<tr>
<td>Postoperative</td>
<td>2.62 ± 0.43</td>
<td>2.19 ± 0.37</td>
</tr>
</tbody>
</table>

**Table 2** Sternochondroplasty: results reported in the English literature.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Type of intervention</th>
<th>Number of patients</th>
<th>Complications (%)</th>
<th>Satisfactory results (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shamberger</td>
<td>1987</td>
<td>PC + PA</td>
<td>152</td>
<td>3.9</td>
<td>98</td>
</tr>
<tr>
<td>Shamberger</td>
<td>1988</td>
<td>PE</td>
<td>704</td>
<td>4.4</td>
<td>94</td>
</tr>
<tr>
<td>Haller</td>
<td>1989</td>
<td>PE</td>
<td>664</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>Fonkalsrud</td>
<td>2000</td>
<td>PE</td>
<td>375</td>
<td>12</td>
<td>97</td>
</tr>
<tr>
<td>Our series</td>
<td>2012</td>
<td>PE + PC + PA</td>
<td>205</td>
<td>12.9</td>
<td>97.5</td>
</tr>
</tbody>
</table>

PE: pectus excavatum; PC: pectus carinatum; PA: pectus arcuatum.
using a "‘vacuum bell’" [3] and dynamic external compression of protruding deformities [12].

The natural history of pectus excavatum studied by Humphrey and Jaretski [13] is the best indicator of the most appropriate treatment. These authors observed an improvement or disappearance of the pectus excavatum in 66% of the cases during the 1st year of life, then an improvement in 40% of patients who were seen between 1 and 13 years of age. Beyond that, the condition was stable (69%) or worsened (31%). As a consequence, we suggest orthopedic treatment in children before or close to puberty, which is effective thanks to the plasticity of the thorax. Being less effective after puberty, it is used as a temporary solution, before sternochondroplasty performed at the end of the adolescent growth spurt. Indeed, resection of rib cartilages too early may lead to severe problems in the development of the rib cage [14].

Surgery should respond to two necessities: correction in accordance with the pathogenesis (excess cartilage length) and minimal surgical risk. In this respect, the Nuss technique, which gives satisfactory results in children with a malleable thorax, on condition that the bars provide adequate stabilization [15,16], does not respond to either of these criteria in the adult: the absence of reduction of excess cartilage length, which is fixed, results in overcorrection, as acknowledged by its instigator [10], or in persistent asymmetry, corrected with subsequent sternochondroplasty [17]. Moreover, multiple serious complications are regularly reported [18–26]. On the other hand, the filling technique [11] leads to no major risk but should be only reserved for moderate forms of pectus excavatum, with no cardiac compression or displacement related to the deformity of the chest wall. Like others [27], we have demonstrated the benefit of restoring the proper anatomy of the chest wall with regard to the cardiovascular adaptation and exercise tolerance, probably as a consequence of the improved filling of the right heart chambers (Fig. 1a, b) and the significant increase in the left ven tricle ejection fraction [28]. Finally, long-term follow-up in adults with pectus excavatum showed 11.5% deaths from cardiocirculatory causes directly or indirectly attributable to the absence of chest wall correction. [13].

The incidence of PFO discovered by transthoracic echocardiography is estimated at approximately 10% in the general population [29]. It may be associated with rare but severe complications, such as strokes of the young subject (one patient in the present study had a history of stroke). The higher PFO rate observed in our series of pectus excavatum (17.5%) suggests a mechanism of mediastinal shift and redistribution of the inferior vena cava blood flow through the septal defect [5,29]. Realigning the mediastinum in a proper position by remodeling the chest wall resulted in PFO closure in nearly two-thirds of the cases, leading to an echo graphic patency rate equal to what is habitually observed in a normal population [29].

Some sternochondroplasty techniques involve major surgery [30]. Our less invasive technique is characterized by small skin incisions [31] and the discontinuation of some procedures such as resection of the xiphoid process, extensive retrosternal dissections, multiple sternal osteotomies, and chest tube placement. Moreover, thanks to careful preservation of the perichondrium, bleeding is minimal during rib cartilage resection, allowing synchronous surgery under cardiopulmonary by-pass with no risk of hemorrhage [6]. Postoperative pain is moderate, permitting rapid discharge from the hospital (approximately 4 days). Finally, removal of the metallic strut does not require opening the initial incision [30].

In the English literature, the "‘excellent’" and "‘good’" results are pooled as "‘satisfactory’" results: our present study is in line with prior published series [32–35] (Table 2).

Conclusion

Better knowledge of the natural history, functional consequences, and orthopedic and surgical treatment possibilities for chest wall deformities should increase their management, which is currently insufficient with regard to their prevalence. Sterochondroplasty is a therapeutic approach in accordance with their pathogenesis, which can be applied to different forms of pectus deformities. Reserved for adult cases, it provides satisfactory cosmetic results with low morbidity and no mortality. Finally, it corrects the anatomical and cardiocirculatory disorders associated with pectus excavatum.

Disclosure of interest


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