Recent Experience With Open Repair of Pectus Excavatum With Minimal Cartilage Resection
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Hypothesis: Inconsistent results have been reported using a variety of open surgical techniques to correct pectus excavatum (PE) deformities with subperiosteal resection of deformed costal cartilages.

Design: Retrospective 3¾-year review of 450 consecutive patients undergoing PE repair.

Setting: Tertiary care academic medical center.

Patients: Symptomatic patients with severe PE (severity index > 3.4).

Intervention: Evaluation of open repair with minimal cartilage resection, suture reattachment of costal cartilages to the sternum and ribs, and internal support strut for 6 months.

Main Outcome Measures: Age at repair, severity index, reduction of symptoms, complications, recurrence, and mortality.

Results: Nine percent of patients were younger than 12 years at repair, 42% were aged 12 to 17 years, 33% were aged 18 to 30 years, and 16% were older than 30 years. Nineteen percent were female. Mean ± SD severity index was 4.88 ± 1.8. Mean hospital stay was 2.9 days. No patients received epidural analgesics. Complications occurred in 2.6% of patients and included idiopathic ventricular arrhythmia (2 patients), transient pericarditis (2 patients), pleural effusion (3 patients), dislodged sternal bar (2 patients), hematoma (1 patient), seroma (1 patient), and localized infection (1 patient). Mild recurrence occurred in 4 patients, and 9 patients had resection of localized cartilage protrusion when the bar was removed. There were no deaths. Ninety-eight percent of patients reported very good to excellent results. All patients reported improvement in symptoms. Mean follow-up was 26 months after strut removal.

Conclusion: In this largest, to our knowledge, recently reported series of openly repaired PE using minimal cartilage resection and suture reattachment of the costal cartilages to the sternum and ribs, advantages included short operative time, stable early postoperative chest wall, few complications, mild pain, good physiologic and cosmetic results, and effectiveness for all variations of PE in patients of all ages.

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Pectus Excavatum (PE) is one of the most common major congenital anomalies, occurring in approximately 1 in every 400 white male births.¹ The deformity appears to be caused by an accelerated growth of the involved costal cartilages compared with the bony ribs and sternum, most likely related to a genetic factor. The lower 4 to 6 of the 7 costal cartilages that attach to the sternum elongate, particularly during the adolescent growth spurt, and push against the sternum, causing it to depress (PE) or protrude (pectus carinatum) or the cartilages to buckle outward. Approximately 7% of patients will have a combination of PE and pectus carinatum. Severe PE deformities cause physiologic limitations as well as adverse cosmetic and psychological effects.²⁻⁵ Patients with severe PE experience dyspnea with exercise, reduced endurance, and often have chest pain. During physical exertion, patients commonly experience tachypnea and have wider diaphragmatic excursions to compensate for diminished chest wall expansion with respiration. In severe cases of PE, compression of the heart with displacement into the left side of the chest results in reduced stroke volume and cardiac output with compensatory tachycardia. One detailed physiologic study by our group showed the aspects of these cardiovascular impairments on exercise performance.³ Symptoms often increase in severity until the patient achieves full skeletal growth at which time the deformity and symptoms often stabilize but do not regress.⁶ As patients progress through adulthood, they often experience increasing symptoms.

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In recent years, surgeons have reported inconsistent results using a variety of open surgical techniques for the correction of PE that have been based on the reports by Ravitch,7 Welch,8 Haller et al,9 and others10 who have recommended extensive subperiosteal resection of deformed costal cartilages with elevation of the sternum using a variety of techniques. During the past decade, patients’ interest in surgical correction of pectus chest wall deformities has increased with the advent of the innovative, minimally invasive PE repair described by Nuss and associates11 and the widespread dissemination of information to patients regarding symptoms from PE and the physiologic improvement following repair as indicated by informative pectus Web sites. Many patients of all ages, including adults, have become aware that their deformities can now be corrected with a higher degree of success and lower risk for morbidity than in previous years.

The present report summarizes our clinical experience with a progressively modified open repair for PE deformities with minimal cartilage resection in 450 consecutive patients during a 6½-year period. Prior to this study, the majority of patients had subperiosteal resection of all deformed costal cartilages with detachment from the side of the sternum.10 Consent for the study was granted by the University of California, Los Angeles Medical Center institutional review board.

### METHODS

During the period from February 1999 through November 2005, 450 consecutive patients underwent repair of PE deformities at the University of California, Los Angeles Medical Center, by the same attending surgeon (Table 1). There were 365 males (81%) and 85 females (19%) ranging in age from 2 to 67 years (mean, 21 years). Since children younger than 12 years typically only have mild symptoms and the costal cartilages are very immature, we recommended repair in this age group only for those patients with severe deformities and not for primarily cosmetic benefits. All patients selected for surgical correction had experienced progressive symptoms, including dyspnea (97%), decreased endurance (98%), tachypnea (73%), tachycardia (71%), and anterior chest wall discomfort (47%). All patients had varying degrees of displacement of the heart into the left side of the chest on radiography or computed tomography. Thirty-seven patients were referred for repair of severe recurrent PE deformities. Nine percent of patients were younger than 12 years at repair, 42% were 12 to 17 years of age, 33% were 18 to 30 years of age, and 16% were older than 30 years. The mean severity index (width of the chest divided by the distance between the sternum and the spine) was 4.88 and ranged from 3.4 to 14.4. The normal chest has a severity index of approximately 2.54, regardless of age.12 The pectus severity index has been derived by radiography or computed tomography of the chest or, more recently, by dynamic magnetic resonance imaging.

Patient characteristics, including sex, age at repair, preoperative symptoms, severity index, postoperative course, and results, were obtained by retrospective medical record review. Patient follow-up was obtained through communication during office visits or via telephone or e-mail.

The details of the operative technique used for the patients in this study have been gradually modified during the 6½-year period to progressively reduce the amount of costal cartilage resection and also reduce the intrusiveness of the sternal support strut.13 General endotracheal anesthesia was administered and an orogastric tube placed in all patients. In patients 12 years and older, a Foley bladder catheter was placed. Intravenous cephalosin was given 1 hour preoperatively. The repair includes the following essential features:

1. A chevron inframammary incision was made with a short midline extension superiorly in all patients who had more than 4 deformed costal cartilages. In female patients, the incision was placed in the submammary sulcus. Most patients younger than 12 years had reconstruction of the lower 4 cartilages, whereas 79% of those older than 12 years had 5 cartilages reconstructed, and 16% had 6 cartilages repaired.

2. Short skin flaps were elevated superiorly and inferiorly using needle-tip electrocautery.

3. The pectoralis muscles were reflected laterally and the abdominal muscles were mobilized inferiorly just sufficient to expose the deformed costal cartilages. For 285 patients, short vertical incisions through the midrectus muscle on 1 or both sides provided exposure to allow reconstruction of the lowest protruding cartilage.

4. Short cautery incisions (5-25 mm) were made in the perichondrium of the deformed cartilages adjacent to the sternum medially and near or beyond the costochondral junction laterally where the chest wall was at the highest level.

5. Short segments of cartilage were resected medially and laterally from each of the deformed cartilages using Freer elevators, with care taken to preserve the perichondrium. For the initial 234 of 450 patients, cartilage segments of 12 to 20 mm were resected medially and laterally, whereas in the last 216 patients, segments of 3 to 10 mm were excised depending on the severity of the deformity. For most patients with severe asymmetric or broad saucerlike deformities, it was necessary to resect segments of a few bony ribs lateral to the costochondral junction to obtain optimal contour. Shorter cartilage segments were removed from the uppermost deformed cartilages. For cartilages with a deep depression in the midportion, an additional chip was removed at that site to permit straightening. For the last 216 patients, the length of the cartilage chips removed was just sufficient to prevent the costal cartilage from pressing against the elevated sternum or the ribs laterally.14 For younger patients, a 1- to 2-mm gap was left at each end to anticipate further adolescent costal cartilage growth without causing recurrent deformity.

6. The xiphoid and the lower 2 perichondrial sheaths were detached from the lower sternum. The remaining perichondrial sheaths and intercostal muscles were left attached to the sternum. A short segment of xiphoid was resected when elongated.

7. The retrosternal space was mobilized from 3 to 5 cm with electrocautery. The pericardium was not entered in any patients.

8. For 322 of 450 patients, the right pleural space was opened for drainage, and a small chest tube was inserted.

### Table 1. Demographics of Patient Population

<table>
<thead>
<tr>
<th>Demographic</th>
<th>No. (%) of Patients*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age range, y</td>
<td></td>
</tr>
<tr>
<td>2-11</td>
<td>39 (9)</td>
</tr>
<tr>
<td>12-17</td>
<td>188 (42)</td>
</tr>
<tr>
<td>18-30</td>
<td>149 (33)</td>
</tr>
<tr>
<td>31-67</td>
<td>74 (16)</td>
</tr>
<tr>
<td>Age, y, mean ± SD</td>
<td>21 ± 10</td>
</tr>
<tr>
<td>Optimal age, y, range</td>
<td>12-19</td>
</tr>
<tr>
<td>Male</td>
<td>365 (81)</td>
</tr>
<tr>
<td>Female</td>
<td>85 (19)</td>
</tr>
</tbody>
</table>

*Unless otherwise indicated.
9. Using a Stryker saw, a transverse wedge osteotomy was made across the anterior table of the sternum at the level where the sternum angled to depress posteriorly.

10. The posterior table of the sternum was gently fractured at the osteotomy without detachment and the lower end of the sternum was then twisted, if indicated, for asymmetric deformities and elevated to the desired position.

11. Nonabsorbable sutures were placed through the anterior table of the sternum across the osteotomy to enhance hemostasis and stability.

12. For 322 patients, a thin stainless steel Adkins strut (Baxter Healthcare Corp Operating Room Division, McGraw Park, Ill) with a slight convex curvature was placed across the lower anterior chest wall posterior to both the sternum and the costal cartilages on each side to elevate the sternum as well as the anterolateral chest to the desired level. The strut was attached to the anterior surface of the appropriate rib on each side with fine wire after resecting an 8-mm segment of costal cartilage laterally and making a small opening in the perichondrial sheath for the bar to exit.

13. For 99 of the most recent patients as well as 29 of 37 recurrent deformities, the strut was placed anterior to the cartilaginous repair and a large stainless steel wire was placed around the sternum and attached to the strut to provide stability (Figure 1).

14. Finely minced segments of the cartilage or bone chips that had been removed earlier were then placed in the perichondrial sheaths where the cartilages did not make contact with the sternum or the rib laterally and at the sites where the strut exited from the thorax, to enhance cartilage regeneration.

15. The xiphoid and lower perichondrial sheaths were sutured back to the sternum with fine wire.

16. For the last 216 patients, the medial ends of the deformed cartilages were reattached to the side of the sternum with nonabsorbable suture or fine wire; the lateral ends were attached to the appropriate rib with nonabsorbable sutures or wire to provide immediate stability.

17. For 4 patients with recurrent PE deformities, 2 anterior struts were used. For 17 tall patients, in addition to the retrosternal strut, a second strut was placed anteriorly across the lower chest caudad to the xiphisternal junction to elevate the lower cartilages, which often had a central depression, using large absorbable sutures.

18. For those 128 patients with an anterior sternal strut who had a small pneumothorax noted during the operation, a small catheter was placed into the pleural cavity through the wound and then removed after the muscle layer had been closed while positive pressure was applied to the endotracheal tube and suction applied to the catheter.

19. For the 128 patients in whom the pleural space was not drained, a small suction drainage catheter was placed between the skeletal and muscle repairs.

20. The pectoralis muscles were approximated in the midline and the abdominal muscles were attached to the pectoral-
lis muscles across the lower chest with absorbable sutures to completely cover the cartilaginous repair.10

21. Thorough hemostasis was achieved with electrocautery, and the wound was copiously irrigated with cephalozin solution throughout the operation.

22. The skin was closed with absorbable subcutaneous and subcuticular sutures supported by Steri-Strips (3M, St Paul, Minn).

The endotracheal tube was removed in the operating room for almost all patients, and the orogastric tube was removed in the recovery room. Two patients remained in the recovery room for 24 hours, and 2 additional patients were placed in an intensive care unit for 24 hours. Postoperative care adhered to an established clinical pathway program to minimize medical errors and reduce costs. Chest tubes and Foley catheters were removed within 24 hours. The wound drains were removed 5 days postoperation in the office. Intravenous cephalozin was given for 3 days and oral cephalaxin was given for 4 additional days. Postoperative pain was managed with intravenous patient-controlled analgesics for the first 48 hours and then by oral non-narcotic medications thereafter. Epidural analgesics were not used in any patients during or after operation. Glucosamine with chondroitin sulfate was given to all patients once daily for 4 months to enhance cartilage regeneration.

The mean duration for repair was 183 minutes, with longer times used for older patients, for those requiring reconstruction of 6 cartilages on each side, and for those with recurrent PE. The mean hospital stay was 2.9 days. Only 4 patients were hospitalized for 4 days. The mean blood loss was 114 mL and for recurrent deformities, 148 mL. None of the patients received a transfusion. All patients were advised to gradually increase both aerobic exercise and weight training within 3 weeks but to minimize twisting of the chest wall or elevating the arms over the head rapidly for 5 months postoperation.

The sternal struts were removed a mean of 6.3 months after repair; adults and patients with recurrent deformities had the struts removed 7 months postoperation. A 2-cm incision on the left side of the chest was used for 93% of all patients, with a second small incision through the midline scar used to remove the large wire around the sternum in patients with an anterior strut. The fine wires used to attach the ends of the strut to the ribs typically fracture within 3 months, making it possible to remove the strut through 1 small lateral incision. All struts were removed on an outpatient basis under light general anesthesia using a laryngeal mask technique and rarely required more than 20 minutes. Patients resumed full physical activities, including body contact sports, following strut removal.

RESULTS

Patient follow-up was obtained through communication during office visits or by telephone or e-mail a mean of 26 months following repair. More than 98% of patients reported very good to excellent results, with diminished symptoms and increased exercise tolerance, reduced dyspnea, increased endurance, reduced chest pain, and reduction of tachypnea and tachycardia within a few weeks following repair (Figure 2 and Figure 3). Symptoms improved further after removal of the sternal struts.

Figure 2. A 23-year-old, symptomatic male patient. A, Patient before repair, with a severity index of 8.1. B, Chest appearance 2 months after removal of the sternal strut.
No patients indicated that symptoms were not improved following repair. There were no deaths intraoperatively or during the period of follow-up. The chest wall was stable immediately following repair in almost all patients who had suture approximation of the costal cartilages to the sternum and the ribs laterally. Those who had larger segments of cartilage excised with cartilage chips placed in the perichondrial sheaths experienced slight paradoxical movement for a few weeks.

Postoperative complications occurred in less than 5% of patients and included idiopathic ventricular arrhythmias during operation, requiring a single electrical shock for cardioversion in 2 patients (Table 2). Transient idiopathic pericarditis responding to a short course of β-blockers occurred in 2 patients. Vigorous physical activities (eg, skateboarding) within 6 weeks postoperation caused dislodgement of the sternal bar in 2 patients; neither developed a pneumothorax and the bars were removed within 5 months after repair. Transient pleural effusion in the right side of the chest occurred in 3 patients, although none required another chest tube. One patient had an anterior chest wall hematoma requiring evacuation within 48 hours. One patient had a seroma, and another had a wound infection treated successfully with oral antibiotics. At the time of strut removal, 28 patients had mildly hypertrophic scars that were treated with injection of triamcinolone solution (10 mg/mL). One patient underwent scar revision. It is our current practice to have patients apply Mederma gel (Merz Pharmaceuticals, Greensboro, NC) to the scar twice daily for 3 months postoperation.

Four male patients from the initial 234, 2 of whom were younger than 12 years at the time of repair, underwent reoperation for mild to moderate recurrence within 4 years. None of the patients who had suture approximation of the shortened costal cartilages to the sternum and to the ribs laterally experienced recurrent depression sufficient to even consider reoperation. Nine patients underwent resection of localized persistent protrusion, most often the lowermost or the second costal cartilage, at the time of strut removal on an outpatient basis. Complications and reoperations were more than twice as frequent when the costal cartilages were not sutured back to the sternum and ribs.

**COMMENT**

The major early concepts for PE repair attributed to Ravitch, Welch, Haller et al, and others included (1) resection of the deformed costal cartilages with preservation of the perichondrial sheaths to permit regeneration...
The wide variation of methods for open repair of PE deformities, frequently referred to as the Ravitch technique, together with many different techniques and devices used to stabilize the chest wall used by different surgeons, even in recent years, has produced results that have been inconsistent, with recurrence being moderately frequent. Reports recommending technical improvements in the basic open repair of PE have been sparse during the past several years. The thin metallic strut developed by Adkins and Blades has been used by many surgeons, including those in the present study, because of its effectiveness and the ease of placement and removal. A mild convex curvature in the strut allows the anterior chest to be elevated to the desired level for optimal contour. Although we have placed the strut posterior to the sternum and costal cartilages in past years and in the first 322 patients in the present series, this has required entering the right side of the chest for proper placement of the strut and the use of an external chest tube for 24 hours. For the last 99 consecutive patients, as well as for 29 with recurrent deformity repair, the strut was placed anterior to the sternum and secured with a large wire, making it unnecessary to enter the pleural space, which further reduced postoperative discomfort. After the metal strut is removed, the cartilages appear to regain near-normal flexibility with respirations as observed in dynamic magnetic resonance imaging studies in 5 recent patients. Six months with sternal support has been sufficient to permit complete healing of the junctions between the costal cartilages and the sternum and ribs laterally for all patients, although we prefer at least 7 months for patients with recurrent deformities and those older than 30 years.

It is common for patients with severe PE to have moderate to severe protrusion of the lowermost costal cartilage on 1 or both sides. In these patients, it is helpful to remove a segment of cartilage at the desired level laterally as well as another segment of cartilage in the midportion, which will allow the reconstructed cartilage to have a more flat contour. Similarly, several patients with severe asymmetric PE deformities will have an unusually deep depression on 1 side, typically the right, in which case it may be necessary to remove a small segment at the depth of the deformed cartilage as well as at either end, such that when reconstructed, the cartilage will appear straight. It is important that the resection of deformed cartilages be extended more laterally in patients where the most elevated portion of the anterior chest is located, such that a small segment of bony rib is resected rather than cartilage medial to the costochondral junction in order to provide optimal contour to the anterior chest. For patients who have a persistent localized protrusion typically in the second cartilage or the lowest cartilage on 1 or both sides after repair, localized subperiosteal resection can be easily performed at the time of strut removal.

Retention of a major portion of the deformed costal cartilages after removing 12 to 20 mm from both ends, as performed in the first 234 patients, left a short segment of perichondrial sheath, which was filled with autologous cartilage chips to enhance cartilage growth. This modification produced a more rapid and consistently stable chest wall than when the entire deformed cartilage was resected in previous years. Without rigid attachment of the costal cartilages at both ends, however, several patients experienced irregularity and discomfort at these junctions. The next 216 patients had suture attachment of the slightly shortened costal cartilages to the elevated sternum and the ribs laterally, which provided immediate chest wall stability and more rapid complete healing with less postoperative pain. Since the major deformity of PE appears related to the accelerated growth of the deformed costal cartilages compared with the bony ribs and sternum, we have observed that resecting just enough cartilage from each end to prevent any pressure on the sternum or ribs laterally permits rapid healing without the need for extensive cartilage regeneration. For younger children with severe deformities, it is particularly important to resect sufficient cartilage to anticipate subsequent growth without developing a recurrent deformity. The retained costal cartilages continue to main-

<table>
<thead>
<tr>
<th>Table 2. Perioperative Course</th>
<th>No. (%) of Patients*</th>
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</thead>
<tbody>
<tr>
<td>Hospital stay, d, mean ± SD</td>
<td>2.9 ± 0.4</td>
</tr>
<tr>
<td>Epidural analgesia</td>
<td>0</td>
</tr>
<tr>
<td>Blood transfusion</td>
<td>0</td>
</tr>
<tr>
<td>Death</td>
<td>0</td>
</tr>
<tr>
<td>Complications</td>
<td>12 (2.6)</td>
</tr>
<tr>
<td>Idiopathic ventricular arrhythmia</td>
<td>2</td>
</tr>
<tr>
<td>Transient pericarditis</td>
<td>2</td>
</tr>
<tr>
<td>Pleural effusion</td>
<td>3</td>
</tr>
<tr>
<td>Dislodged sternal bar</td>
<td>2</td>
</tr>
<tr>
<td>Anterior chest wall hematoma</td>
<td>1</td>
</tr>
<tr>
<td>Wound infection</td>
<td>1</td>
</tr>
<tr>
<td>Seroma</td>
<td>1</td>
</tr>
<tr>
<td>Mildly hypertrophic scar</td>
<td>28 (6.2)</td>
</tr>
<tr>
<td>Mild recurrence reconstructed</td>
<td>4 (1)</td>
</tr>
<tr>
<td>Protruding costal cartilage revision at time of strut removal</td>
<td>9 (2)</td>
</tr>
</tbody>
</table>

*Unless otherwise indicated.
tain much of the flexibility in the anterior chest compared with the regenerated, more rigid structures that develop when the perichondrial sheaths are relied on for complete regeneration of the ribs. Reoperation on the 37 patients referred with recurrent PE, all of whom had previous resection of all the deformed costal cartilages, confirmed the very rigid and calcified ribs that were produced by the perichondrial sheaths. Any damage to the perichondrial sheaths during the extensive resection of cartilages may result in a somewhat incompletely regenerated rib.

Although only the 7 upper costal cartilages attach directly to the sternum, only the lower 4 cartilages appear deformed in the majority of preadolescent patients. Thus, many surgeons reconstruct only the lower 4 cartilages in patients of all ages with PE. As children progress through the years of rapid adolescent skeletal growth, the costal cartilages of patients with PE typically experience an accelerated growth compared with the bony ribs, resulting in increasing severity of the deformity. Additionally, during this period it is common for the third and occasionally the second cartilage to become deformed, which may be in part responsible for the development of recurrence in patients who underwent primary repair before age 10 years. In the present series, 34 of the 37 patients who were referred for repair of recurrent deformities had the primary repair before the age of 10 years. The average age at the time of repair in the present report was 21 years, which reflects our view that asymptomatic patients younger than 12 years with mild deformities should have repair deferred until more advanced skeletal growth has occurred. In the present series, 79% of patients older than 12 years had reconstruction of 5 cartilages on each side, and 16% had 6 cartilages repaired. Only 9% of patients in this report underwent repair at younger than 12 years; each was symptomatic and had a severe deformity.

Longer follow-up will be necessary to determine if the results observed in this study are maintained for many years. It is difficult to compare the results in this study accurately with those with the Nuss procedure, since each technique has a definite learning curve and the patient selection is quite different. The Nuss procedure is used primarily for younger children with symmetric PE, whereas the open technique is equally effective for patients of all ages with PE. Since the Nuss bars are placed beneath the perichondrial sheaths during the extensive resection of all the deformed costal cartilages, considerable rib damage may result in a somewhat incompletely regenerated rib.

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REFERENCES