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912 Open Pectus Excavatum Repairs: Changing Trends, Lessons Learned: One Surgeon's Experience

Eric W. Fonkalsrud

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Abstract
Background Severe pectus excavatum (PE) is common, often causing physiologic impairment. Inconsistent results have been reported using a variety of open surgical techniques with extensive subperiosteal costal cartilage resection.
Methods Since 1969, 912 (80% men) symptomatic PE patients (mean severity index 4.9) underwent open surgical correction at UCLA Medical Center by one surgeon. Almost all patients had dyspnea, reduced endurance, tachypnea, and tachycardia with exertion. The mean age at operation was 19.8 years. Asymmetric depression was present in 465 (51%) patients; combined PE and pectus carinatum was present in 33 patients. Recurrent PE deformities were repaired on 73 patients. Progressively less deformed costal cartilage was resected during the 38-year period; almost all of the last 303 patients had only short segments excised from both ends with suture reattachment. Transverse wedge sternal osteotomy was used on all patients, and 883 (97%) had a sternal support strut for 6 to 9 months.
Results Dyspnea, endurance, tachypnea, and tachycardia was improved in almost all patients within 5 months after repair. Repair for recurrent deformities and resection of mild localized cartilage protrusion was reduced more than threefold when minimal cartilage resection with wire reattachment was used. Postoperative complications in the last 537 patients were less frequent, pain was less severe, and results were better than when more extensive previous repairs were used (mean follow-up 7.6 years). Very good or excellent results were reported by 94.2% of all patients.
Conclusions In this largest series of open PE repair, progressively less extensive operative techniques have resulted in low morbidity, mild pain, short hospitalization, and very good physiologic and cosmetic results.

Introduction

Pectus excavatum (PE) depression deformities are among the most common major congenital anomalies, occurring in approximately 1 in 400 white male births [1]. Most PE deformities are first recognized in infancy and slowly become more pronounced with considerable increase in severity during adolescence until full skeletal maturity is achieved, after which little change occurs throughout adulthood [2, 3]. Spontaneous regression is extremely rare. The deformity occurs more frequently in Caucasians, and is uncommon in blacks, Latinos, and Asians. Pectus excavatum is approximately five times more common than pectus carinatum (PC) and is less common in women [2, 4]. Other malformations may coexist, especially scoliosis, and occasional musculoskeletal anomalies or connective tissue disorders. Most PE patients are tall, have an asthenic habitus, and a slouching posture. The chest characteristically has a decreased anterior to posterior diameter [4]. The lowermost cartilages commonly flare outward, giving younger patients a "potbelly" appearance.

One prevalent theory regarding the development of both PE and PC is that there is a genetic predisposition for disproportionate growth of the costal cartilages compared with the remainder of the thoracic skeleton, which exerts pressure on the sternum to cause depression, protrusion, or

E. W. Fonkalsrud (✉)
Department of Surgery, UCLA Medical Center, 10833 LeConte Avenue, Los Angeles, CA 90095, USA
e-mail: efonkalsrud@mednet.ucla.edu

combination of both [4, 5]. Pedigree analysis of many families provides evidence that PE is an inherited disorder, possibly of connective tissue [6]. The histologic appearance of deformed cartilages is almost always normal.

Symptoms from PE are infrequent during early childhood, apart from an unwillingness to expose the chest. Almost all patients with severe PE indicate that they have progressive symptoms of early fatigability, dyspnea, decreased endurance, tachycardia and tachypnea with physical exertion, particularly during the period of rapid adolescent growth; many experience pain in the anterior chest. Exercise-induced wheezing and lightheadedness are occasionally reported during extensive exercise [7]. With moderate-to-severe PE, the heart often is displaced into the left chest and compressed, causing reduced stroke volume and cardiac output during exertion [8]. Pulmonary expansion during inspiration is moderately confined, resulting in restriction, which often is noted on exercise pulmonary function tests [9]. Severe PE deformities cause physiologic restriction for patients and are not merely a cosmetic concern.

The pectus severity index (PSI) (width of chest divided by the distance between the posterior surface of the sternum and the anterior surface of the spine at the same level) determined on chest radiographs or computed tomography (CT) scans, as described by Haller et al. [10], is the most commonly used method of determining the severity of PE and PC deformities. The normal chest has a PSI of approximately 2.54, and patients who underwent PE repair had a PSI of 4.4 [10]. The narrow anterior to posterior (AP) diameter of the chest in many PE patients may make the index more severe. Other methods for determining PE severity are more complex, less helpful, and often more expensive.

Respiratory excursions of the thorax in patients with PE, comparing maximal inspiration to maximal expiration, are commonly reduced. Most symptomatic PE patients have more extensive phrenic excursions during exercise than when the normal chest expands. Many studies performed during the past four decades have failed to document consistent improvement in pulmonary function at rest after surgical repair of PE, despite considerable symptomatic improvement [11, 12]. Patients with PSI >4.0 are eight times more likely to have reduced aerobic capacity than patients with low PSI, despite their level of exercise participation [8]. Further studies during exercise have shown that maximum voluntary ventilation, maximum oxygen utilization, total lung capacity, and total exercise time are improved significantly after PE repair [9]. Physiologic impairment and reduced exercise capacity is primarily the result of impaired cardiovascular performance rather than ventilatory limitation, which is not explained by physical deconditioning [13]. Right axis deviation and depressed ST segments are common with severe PE, which reflects rotation and compression of the heart rather than an intrinsic abnormality. Compression of the right ventricular outflow tract may cause a functional systolic murmur. Cardiac ECHO studies have demonstrated mitral valve prolapse in approximately 11% of patients [3].

Ventricular catheterization studies have demonstrated diminished stroke volume and cardiac output in preoperative patients during upright exercise [14, 15], which improved considerably after repair [16, 17]. These findings are not demonstrable in supine patients evaluated at rest and may account for some of the reports of minimal physiologic impairment in PE patients. Dynamic magnetic resonance imaging studies of the heart, chest wall, diaphragms, and lungs may be more definitive in identifying physiologic changes in dynamics caused by PE, as well as improvement after repair. An extensive 3-year study of approximately 30 patients with PE using this technique before and after repair is near completion in our hospital. The significance of cardiac compression and displacement on older patients is speculative, although stroke volume and cardiac output have been shown to be reduced [14, 18].

Many patients and their families have been poorly informed by physicians about the limiting physiologic effects of PE deformities or the availability of safe and successful options for surgical repair. Although most patients are concerned about physical limitations, many also are displeased about having a poor body image. Repair of the thoracic skeleton is rarely recommended for cosmetic improvement alone, unless less extensive cosmetic enhancement procedures are not feasible. The availability of several websites on the Internet regarding pectus deformities during the past several years has allowed patients to become better informed and to obtain advice from other patients and from knowledgeable physicians.

Surgical correction

In previous years, many surgeons recommended that many minimally symptomatic children with mild-to-moderate PE undergo repair between the ages of 2 and 6 years, because repair can be easily performed at this young age, and family concerns are alleviated. Early repair of PE by techniques that resect the major portion of deformed costal cartilages have been discouraged in the past several years, because this may interfere with rib growth plates and produce a narrow chest [19]. Haller and associates [20] have cautioned against extensive cartilage resection in young children because of the occasional later occurrence of constricting asphyxiating thoracic dystrophy. Young children who undergo repair of only the lower three or four costal cartilages that appear deformed may experience later depression

of one or more higher cartilages resulting in recurrent PE as they progress through the adolescent growth period. Many surgeons who currently perform the open repair of PE recommend waiting until children are at least 12 to 13 years of age, unless the PE is severe and causes physiologic symptoms earlier. The optimal age for repair appears to be between 13 and 19 years; however, many adults with persistent symptomatic PE extending into the sixth decade have achieved good results after repair [3, 21]. Reconstruction with autologous tissue, or prosthetic materials, for patients with mild deformities may result in improvement in chest contour but provides no physiologic benefit for patients with severe symptomatic PE.

Surgical repair for PE may be performed by using extensive modifications of the original procedure described by Brown [22] and modified by Ravitch [23] and Welch [24], and others, or with minimal costal cartilage resection as described recently [25]. Reports that recommend technical improvement in the open repair of PE have been sparse for the past several years [26, 27]. Minimally invasive repair without costal cartilage resection as described by Nuss and associates [28] has been used with increasing frequency during the past decade. Maintenance of the elevated sternum in the corrected position by external traction using harnesses or other cumbersome devices has been abandoned in favor of various methods of internal fixation. The use of vacuum bell suction and internal magnets is currently under evaluation [29, 30]. Internal sternal support with a temporary metal strut after repair of PE minimizes the occurrence of postoperative respiratory distress caused by paradoxical chest motion, reduces pain, permits early ambulation and permits deeper respirations, and maximizes the extent to which the defect is permanently corrected.

This study was designed to review the experience of one surgeon with 912 patients with symptomatic PE who underwent open surgical repair since 1969. The last 540 patients had a less extensive open repair with minimal cartilage resection. The focus of this report was to indicate in detail the changes in operative technique, which have evolved during this 38-year period, and how they have enhanced the long-term results and reduced complications and length of hospitalization. Consent for this study was granted by the UCLA Medical Center Institutional Review Board.

Methods

During the 38-year-period from 1969 through 2007, 912 patients (730 men, 80%; and 182 women) underwent open surgical correction of PE deformities at the UCLA Medical Center. Repair was performed on 537 patients (59%) during the past 9 years. Asymmetric deformities were present in 465 patients (51%) and 19 patients had a combination of PC in the upper chest and PE in the lower anterior chest. Fourteen patients had mild-to-moderate PC of the left chest and moderate-to-severe PE of the right anterior chest with marked downward twisting of the sternum. Moderate-to-severe protrusion of the lowermost cartilages extending lateral to the anterior axillary line on one or both sides, sufficient to warrant reconstruction was present in 396 patients (43%). Approximately 45% of these patients had depression of the mid portion of the lowermost two cartilages that required correction to achieve optimal contour. Since 1993, 73 patients (8%) underwent repair of recurrent PE deformities, 4 of whom had a previous Nuss repair. The age at the time of surgical repair ranged from 2½ to 67 (mean, 19.8) years, with 268 patients aged 19 years or older (29%). No adults underwent PE repair before 1986.

Almost all patients were in good general health at the time of surgical repair. Mild-to-moderate scoliosis was present in 356 patients (39%), only 8 of whom underwent bracing or spinal correction. Sixty-five patients had mitral valve prolapse (7%). A functional heart murmur was present in 18%; 11 patients (1.2%) had congenital heart disease. Ten patients had Marfan's syndrome, four had Ehlers Danlos syndrome, and three had Stickler's syndrome. Other disorders or minor anomalies were present in 45 patients (5%).

The most frequent symptoms reported by almost all patients older than aged 7 years were dyspnea, diminished endurance, and tachycardia with mild physical exertion, compared with other persons of similar age, as noted previously [4, 25]. Compensatory tachypnea (breathing at a faster rate than peers performing the same exercise) was noted by >98% of patients older than aged 12 years. Symptoms commonly became more severe during the adolescent years, causing progressive limitation in exercise tolerance. There were 173 patients (19%) who experienced exertional wheezing, and 87 patients (9.5%) had asthmatic symptoms that require occasional bronchodilator medications. Recurrent sinusitis was reported by 8%. Children who experienced chronic respiratory distress or pneumonia during infancy or early childhood often experienced more severe symptoms than other patients with deformities of similar severity during adolescence. Concern about the unattractive appearance of the chest was expressed by almost all patients. Approximately 3% of patients, almost all older than aged 18 years and with mild-to-moderate deformity, strongly desired to undergo open repair of PE in the absence of significant symptoms, and most had surgical correction deferred until symptoms were recognized, or were referred to a plastic surgeon for soft-tissue enhancement.

Chest x-rays (62%) or CT scans (38%) were performed on all patients and showed a decrease in AP diameter, a somewhat broad width, and deviation of the heart into the left chest in the majority of patients. The overall PSI ranged from 3.3 to 14.5 (mean, 4.9); group I patients were younger with a mean PSI of 3.9. The decision to repair the PE deformity was based on the severity of symptoms and the PSI.

Operative technique

The operative technique used for the repair of the 912 patients with PE has been a progressively less extensive open repair compared with those described by Ravitch [31] and others, minor modifications of which are in current use by many surgeons [26, 32]. Adequate exposure of the deformed cartilages is considered essential to achieve optimal reconstruction with good long-term results. The technical details of the repair have varied somewhat depending on the degree of asymmetry and the contour of the sternum and have been extensively detailed in previous reports [3, 4, 7, 25, 33].

For the first 29 patients, mean age 6.1 years (group I), through a chevron-shaped incision, the pectoralis muscles were reflected laterally and the rectus muscles were detached from the sternum and lowest costal cartilages by using needlepoint cautery dissection. The lower four deformed costal cartilages were resected subperiostially from sternum to costochondrial junction. The periosteal sheaths and intercostal muscles were detached from the sternum, preserving the internal mammary vessels. The xiphoid was detached from the sternum and the retrosternal space was mobilized with cautery for 3–4 cm. A transverse wedge osteotomy was made across the anterior table of the sternum superior to the level of the highest cartilage resected, using a mallet and chisel. The posterior table of the sternum was gently fractured but left intact; the sternum was then elevated and twisted to the desired position. Heavy nonabsorbable sutures were placed through the anterior sternal table across the osteotomy to secure the sternum in the desired position. The right pleural space was entered in all patients, and a chest drainage tube was placed. The perichondrial sheaths were closed with absorbable sutures and the lower two perichondrial sheaths were brought posterior to the sternum and sutured to the corresponding sheaths from the contralateral side to provide sternal support in 17 patients; no support was used for 12 patients. The remaining perichondrial sheaths, intercostal muscles, and xiphoid were sutured back to the sternum. The pectoralis muscles were approximated in the midline, and then sutured to the abdominal muscles to cover the entire cartilaginous repair with muscle. The wound was irrigated with cephazolin solution throughout the dissection. A small suction catheter was placed between the cartilaginous and muscle repair for 3 days. The chest tubes were removed within 24 hours.

For the next 346 patients (group II), the mean age was 13.4 years. The incision, mobilization of muscles, and sternum were similar to patients in group I, except that only the lower two or three perichondrial sheaths were detached from the sternum. The lower four, and often five, deformed costal cartilages were resected subperichondrially by using a Freer elevator. Short segments of a few bony ribs laterally were resected in patients with a broad or asymmetric deformity. The sternal wedge osteotomy and suture closure were the same as in group I. An Adkins support strut [34] (The Adkins strut formerly produced by V. Mueller, Inc. is no longer available. A very slightly modified Pectus strut is now produced by Koros USA, Inc., 610 Flinn Ave, Moorpark, CA 93021) with slight convex curvature was placed across the lower chest posterior to the sternum but anterior to the closed perichondrial sheaths and then secured to the anterior surface of the appropriate rib on each side with fine wire in 44 patients. The remaining 302 patients had the strut placed beneath both sternum and perichondrial sheaths, exiting through the appropriate sheath at the costochondrial junction to prevent depression of a cartilage on each side. The closure was as described for group I patients. The right pleural space was entered in almost all patients and a chest drainage tube was placed and removed within 24 hours.

The remaining 537 patients (mean age, 20.2 years) included 58 patients with recurrent PE. A chevron incision with a short midline extension superiorly was used in all patients with more than four deformed cartilages (93%). Only the xiphoid and lower two to three perichondrial sheaths were detached from the sternum. The pericardium was not entered in any patient. The mid portion of the deformed costal cartilages was preserved in 234 patients (group III) and segments of 12–20 mm were resected medially and laterally. Finely minced autologous cartilage chips were placed into the perichondrial sheaths to enhance cartilage regeneration. For most patients with severe asymmetric or broad saucer-like deformities, it was necessary to resect segments of a few bony ribs lateral to the costochondrial junction to obtain optimal contour. Shorter segments of cartilage were resected from the uppermost deformed cartilages. For cartilages with a deep depression in the mid portion, an additional chip was removed at that site to permit straightening. The xiphoid was narrowed and often shortened before reattachment to the sternum.

For almost all of the last 303 patients (group IV) the length of the cartilage chips removed (3–10 mm) was just sufficient to prevent the costal cartilages from touching the corrected sternum and the ribs laterally [25]. For younger patients, a 3-mm to 5-mm gap was left at the lateral end to anticipate further adolescent cartilage growth without

causing recurrent deformity. For 297 of the last 537 patients, an Adkins strut was placed posterior to the sternum and costal cartilages as in group II. For the remaining 240 patients, including 46 of the recurrent deformities, the strut was placed anterior to the cartilaginous repair and a large stainless steel wire was placed around the sternum and secured to the strut. The ends of the cartilages were sutured to the sternum medially and to the appropriate ribs laterally with wire sutures. For those patients with an anterior sternal support strut who developed a pneumothorax during the operation, a small catheter was placed into the pleural space through the wound and then removed after the muscle layer had been closed while positive pressure was applied to the endotrachael tube and suction was applied to the catheter. A small suction catheter was placed between the muscle and cartilaginous repairs as in group II.

The endotrachael 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 an additional three older patients were placed in an intensive care unit for 24 hours. Chest tubes and Foley catheters were routinely removed within 24 hours. The small suction catheter between the muscle and cartilaginous repair was gradually advanced outward and removed at the first office visit.

Intravenous antibiotics (cephazolin sodium) were given for 48 hours and oral cephalexin was given for an additional 4 days. Postoperative pain was managed in almost all patients with intravenous analgesics for the first 48 hours and by oral nonnarcotic medications thereafter. Analgesic medications were only occasionally used after 1 week, even in adults. Epidural analgesics were not used in any patients. Postoperative care followed a clinical pathway protocol to expedite care and reduce the frequency of errors. Glucosamine with chondroitin sulfate (500 mg) daily was given to all patients within the past 11 years for 4 months to enhance cartilage regeneration.

The mean duration for repair was 185 minutes, with longer times used for older patients, for those requiring reconstruction of six cartilages on each side, and for those with recurrent PE, but with little difference related to the operative technique used. The mean hospital stay for groups I and II patients was 3.7 days and for groups III and IV it was 2.8 days. Only 7 patients from groups III and IV were hospitalized for 4 days. The mean blood loss was 112 ml. No patients have received a transfusion since 1982.

Sternal struts were removed a mean of 6.5 months after repair; adults and patients with recurrent deformities had the struts removed after 7–9 months. The tip of the strut was located with a portable fluoroscopic unit. A 2-cm incision on the left chest was used for 95% of all patients, with a second small incision through the midline scar to remove the large wire around the sternum. Only 5% of patients—all from groups II and III—required a second incision on the right to mobilize the strut. 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 one small incision. All struts were removed on an outpatient basis under light general anesthesia using laryngeal mask technique and rarely required more than 20 minutes. Patients gradually resumed full physical activities, including body contact sports after strut removal.

Results

Follow-up for the 912 patients who underwent PE repair was performed by office visit, telephone, or e-mail from 3 months to 18 years after sternal strut removal (mean, 7.6 years) and has been provided in previous reports [7, 25, 33]. One hundred three patients (11%) were lost to follow-up within 9 months after strut removal. Reporting symptoms before, and improvements after, repair was subjective and reliant on the patients' response to questions. Ninety-six percent of patients with preoperative dyspnea and reduced endurance and exercise tolerance experienced considerable improvement within 4–7 months after the operation, which often improved further after strut removal. Vital capacity, as determined by repeated incentive spirometer measurements, improved (mean, 10.8%) for the 155 patients tested. Each of the patients with recurrent bronchitis, and those with asthmatic symptoms, indicated fewer episodes of wheezing and bronchitis with a reduced need for medications. Further improvement was noted after sternal strut removal, which permitted more extensive chest expansion and contraction with respirations. Although 22 female patients with asymmetric PE and breast contours had right submammary prostheses, none had breast asymmetry after pectus repair [35]. All except for 29 patients (3.2%), 5 of whom had had repair of recurrent deformities and 11 of whom had had repair when younger than aged 8 years, indicated that they considered the long-term results after final repair to be very good or excellent. Preoperative and postoperative photographs have been published previously [4, 7, 21, 25, 33, 35].

Five patients from group I (17%), 15 patients from group II (4.3%), 7 patients from group III (3%), and 4 patients from group IV (1.3%) developed recurrent PE deformities—22 of whom underwent surgical reconstruction (2.4%). Eight of the reoperated patients were younger than 12 years at the time of the initial repair. Reoperations were more than four times as frequent for groups I-III than for group IV. Mild recurrent depression with a PSI <3.3 occurred in 12% of all patients and was $<4\%$ in group IV; most of these patients experienced only mild, if any, symptoms. Three patients from group I experienced slight

localized narrowing of the mid lateral chest, which has been asymptomatic. None developed evidence of asphyxiating thoracic dystrophy.

Postoperative complications occurred in 8% of all patients. Two patients had idiopathic intraoperative ventricular arrhythmias that required a single electrical shock for cardioversion. Pericardial effusion occurred in three patients, two of whom developed transient idiopathic pericarditis postoperation responding to a short course of beta blockers. Vigorous physical activities (e.g., skateboarding) within 6 weeks after the operation caused dislodgement of the sternal bar in three patients: one required bar removal 3 months after repair, and the other two at 5 months. Two of these patients developed mild recurrent sternal depression. One patient had an anterior chest wall hematoma that required evacuation within 48 hours. Eighteen patients from groups I and II had a seroma, which required one or two aspirations. No patients with a submuscluar drainage catheter developed a seroma. Only 2 of the last 537 patients had more than a 10% postoperative pneumothorax or a pleural effusion that required a single aspiration. Patients with a unilateral pneumothorax <10% and who were asymptomatic received no aspiration. Two of the 912 patients experienced a superficial wound infection, which did not extend to the support strut. There were no deaths among the 912 patients during the period of follow-up. At the time of strut removal, 24 patients underwent resection of a localized cartilage protrusion. Sixty-seven patients had mildly hypertrophic scars that were treated with injection of triamcinolone solution (10 mg/ml). Five patients underwent scar revision during the strut removal. During the last 6 years patients were advised to apply Mederma gel (Merz Pharmaceuticals, Greensboro, NC) to the scar twice daily for 3 months after their operation, which markedly reduced wound scarring.

Discussion

Major features of the operative technique, which have been modified in the repair of PE during our experience during the past 38 years, include the following: repair of PE is performed primarily for relief of symptoms, most frequently reduced endurance, tachypnea, tachycardia, and occasionally discomfort, and rarely for only cosmetic benefit. Nonetheless, almost all patients indicated their gratification for the improvement in body image. Almost all patients with moderate-to-severe deformities (PSI $\geq$ 3.7) experienced moderate-to-severe symptoms. The PSI in most patients with PE can be determined with moderately high accuracy from a PA and lateral chest radiograph. CT scans are limited to patients with unusual or recurrent deformities to minimize the cancer risk from childhood radiation [36] as well as cost. Extensive evaluation of cardiopulmonary function in most patients with symptomatic PE is unnecessary to determine whether repair should be performed and is very costly. Similarly, postoperative chest x-rays and hematologic studies are rarely performed. Adherence to a Clinical Pathway has reduced costs as well as medical errors in our experience. Insurance coverage for PE repair has become increasingly difficult to obtain during recent years, and efforts have been made to reduce overall costs. We prefer to repair PE deformities during early to mid adolescent years when anticipated further skeletal growth is <6 inches in height, and also to allow subsequent participation in vigorous physical activities.

During the past 21 years, 268 adults (29%) underwent repair of severe PE. During the same period, only 59 children younger than aged 11 years underwent repair, in contrast to previous years when almost 50% of repairs were performed for children younger than aged 11 years [33]. Repair in prepubescent children is reserved for the few with severe and symptomatic deformities. The technical repair of PE in adults often is more tedious than in children because of the often partially calcified or brittle cartilages, which occasionally require scooping out with a rongeur or cutting with a saw or bone cutter, and the slower regeneration of cartilage and bone. Nonetheless, the recovery and long-term results have been almost as good as those for adolescents [3, 21].

Ten of the 912 patients with mild-to-moderate PE deformities (PSI <3.8) indicated more severe symptoms than might be expected and requested open repair. Several patients indicated persistent but less severe symptoms with discomfort after repair despite having only mild residual deformity. A few of those patients were almost obsessed with the appearance of the chest and strongly desired further reconstruction of the bony skeleton rather than cosmetic enhancement. Reoperation to alleviate pain has been largely unsuccessful in providing improvement, in our experience, unless there is a localized movement between the cartilage and the sternum or rib, or localized protrusion. Because many patients with mild PE will benefit from soft-tissue reconstruction, it is beneficial to clearly determine the symptoms before performing skeletal repair.

General endotrachael anesthesia was used for all patients with a transient orogastric tube removed in the recovery room to minimize postoperative gastric distention. A Foley catheter was placed for all patients aged 12 years and older for 24 hours to avoid the frequent need for catheterization in the awake postoperative patient. The chevron incision is usually sufficient for patients with four deformed costal cartilages; however, we have not found this adequate to correct five or more deformed PE cartilages optimally in most adolescents and adults. The vertical extension healed as well as the transverse incision in all

patients. Skin flaps were as short as feasible to minimize prolonged loss of skin sensation, usually painless, which is particularly important in women to avoid nipple insensitivity. Most patients will regain near normal sensation within 12 to 16 months. The pectoralis and rectus muscles were elevated with needle tip electrocautery just sufficient to expose the deformed cartilages, which also makes complete muscle coverage of the cartilaginous repair feasible during closure. Muscle closure will conceal small irregularities of the cartilages or sutures. A short vertical incision in the mid rectus muscle on one or both sides often is helpful to gain exposure for optimal repair of the lowermost cartilages.

There is a tendency to underestimate the number of deformed costal cartilages and how far superiorly and laterally to extend the cartilage or bony resection. Almost all adolescent and adult patients with PE needed reconstruction of at least five, and 33% required six, of the lower cartilages attached to the sternum to achieve optimal results. From group I, 27 patients (93%) had only four cartilages reconstructed; six patients experienced mild-to-moderate depression of the third and occasionally the second cartilages and sternum during adolescence. Reconstruction of the first costal cartilage is rarely necessary and is likely to reduce stability of the manubrium, clavicle, and the shoulder joint.

Resection of the entire deformed costal cartilages with preservation of the perichondrial sheaths as performed in groups I and II was discontinued when it was noted that the regenerated cartilage was occasionally thin, irregular, and commonly rigid with varying amounts of calcification and/or bone formation, as noted by others [37]. Even minor damage to the perichondrial sheaths may cause incomplete cartilage regeneration, occasionally producing a somewhat unstable chest. If the sheaths are not closed adequately, the regenerating cartilages may fuse together over the intercostal muscles causing a rigid chest as was observed in 12 patients referred with recurrent deformities, for whom repair was very difficult technically. Removing large segments of costal cartilage in children also may interfere with rib growth plates and produce a narrow chest [19].

Retention of a major portion of the deformed costal cartilages after removing 10 to 15 mm from both ends, as performed in group III, left short segments of perichondrial sheaths, which were filled with autologous cartilage chips to enhance cartilage growth. Flexible cartilage was retained, which produced a more rapidly stable chest wall than when all the deformed cartilages were removed [7]. Approximately 14% of these patients experienced mild-to-moderate instability at one or both ends of one or two cartilages with occasional mild localized protrusion or depression causing discomfort in a few. Minor resection of persistent localized protrusion was reduced from 4% in group II to 1% in group IV.

The last 303 patients (group IV) had suture attachment of the shortened costal cartilages to the reconstructed sternum and the ribs laterally, which provided immediate chest stability and more complete healing with less postoperative pain compared with the earlier techniques. The reconstructed cartilages appear to retain a major portion of the original flexibility used during respiration. Because the PE deformity seems to be related to the accelerated growth of the deformed costal cartilages compared with the bony skeleton, resecting just sufficient cartilage from each end to prevent any pressure on the sternum or ribs laterally seems to permit rapid healing without the need for more than minimal cartilage regeneration. For children in whom at least 3 inches of subsequent growth is anticipated, it is important to leave 3 to 4 mm of space at each end, and then wire the cartilage loosely to the sternum and the ribs laterally without producing a recurrent deformity. When more than 4 to 5 inches of growth is anticipated, in our experience, it has been best to use a variation of the technique described for group III patients with suture attachment of the cartilage to the sternum with a 1 cm space in the perichondrial sheaths laterally, filled with cartilage chips. Patients seem to have a higher frequency of mild recurrent depression if insufficient cartilage is removed.

The costal cartilage resection should extend onto the bony rib lateral to the costochondrial junction on one or more ribs, most often on the right, when necessary to obtain the optimal chest contour. The costal cartilage segments can be readily removed by using Freer elevators and a scalpel, preserving the perichondrial sheaths. A Stryker saw or bone cutters are used to cut bony ribs. Failure to securely attach both ends of the shortened cartilages to the sternum and to the ribs may result in delayed and, occasionally, incomplete or irregular healing, which may cause pain.

A short vertical incision through the rectus muscle on one or both sides may be helpful to expose the lowermost costal cartilages adequately, particularly if there is a more severe depression or protrusion far lateral to the sternum. For lower cartilages that have a prominent depression in the mid portion, it is helpful to resect a triangular wedge of cartilage from the deepest site with the base on the posterior side, and reapproximate with wire to obtain a straight contour (Fig. 1). Similarly, if the lower cartilages protrude outward laterally, a triangular wedge is excised with the base on the anterior surface. Correction of these lower cartilages is very difficult to achieve if an open repair is not performed.

Reattachment of the perichondrial sheaths to the sternum with nonabsorbable sutures may be satisfactory for patients who have had large segments or all of the costal

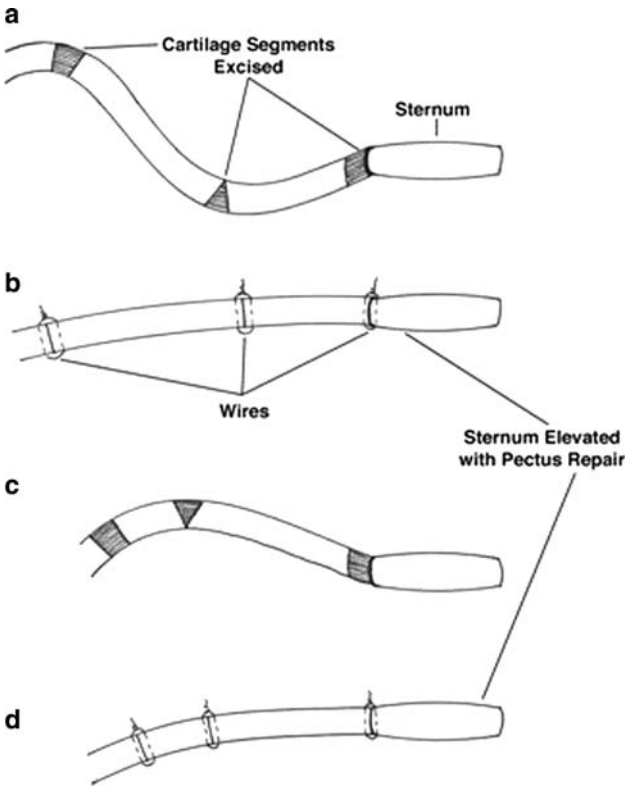

Fig. 1 **a** Transverse view of sternum and costal cartilage with severe depression in mid portion. Cartilage segments removed from medial and lateral ends (group IV). A triangular wedge with the base on the posterior surface is removed from the deepest site on the cartilage. **b** Wire sutures placed across the three sites of cartilage resection to construct a nearly straight costal cartilage after sternum elevated. **c** Lower costal cartilage with severe protrusion laterally. After excising medial and lateral cartilage segments, a triangular wedge with the base on the anterior surface is removed from the most protuberant site on the cartilage. **d** Wire sutures placed across the three sites of cartilage resection to make a nearly straight costal cartilage

cartilages resected and for preadolescent children (groups I–III). Stainless steel wires provide the greatest chest wall stability when the shortened cartilages are sutured directly to the sternum and ribs. A drill is helpful when placing a wire through a bony rib, which might otherwise split. Similarly the sternal osteotomies appear to be held most securely in the desired position with wire rather than sutures in adolescents and adults.

For patients with a PC of the upper and PE of the lower sternum, a transverse osteotomy may be made superiorly and an anterior transverse wedge osteotomy made at the appropriate level, often 6 to 10 cm above the xiphisternal junction, and then stabilizing both osteotomies with wire sutures. For patients with depression of the mid sternum and protrusion of the lower end, a second transverse osteotomy at the appropriate level with placement of a wedge of cartilage and closure with a wire will provide a flat sternum.

The xiphoid in patients with PE, which commonly protrudes posteriorly or anteriorly, was detached to achieve optimal contour, and to gain adequate access to the anterior mediastinum. Only the lowest two to three perichondrial sheaths and intercostal muscles were detached from the sternum to assure good vascularity to the distal sternum. The posterior surface of the sternum was mobilized from the anterior mediastinum over a distance of 5 to 9 cm to facilitate straightening to a flat level and to permit placement of the circumferential wire for securing the sternum to the support strut. For most patients in group IV, the diaphragm was partially mobilized from the posterior surface of the lower cartilages to permit elevation to the desired contour with minimal force. For most patients in groups III and IV, the xiphoid was shortened and narrowed to fit into the space between the lowest cartilages and then sutured to the sternum. The xiphoid is preserved to enhance normal contour in the mid upper abdomen.

We have used the Adkins strut routinely, except for a few patients in our early experience (group I) because of its effectiveness and the ease of placement and removal. The strut is almost always bent with a slight-to-moderate convexity to provide the desired chest contour, particularly for patients with a narrow AP diameter. Although we placed the strut posterior to the sternum and cartilages in earlier years, this has required entering the right chest for proper placement of the strut and the use of an external chest tube for 24 hours. We initially placed the strut anterior to the sternum and cartilages for two patients who had congenital absence of the pericardial sac, which then made it unnecessary to enter the right chest, and reduced postoperative discomfort. The strut has been placed external to the skeletal repair on all subsequent patients (group IV). For older patients with a broad saucer-shaped deformity, two struts held together with absorbable suture were used to give additional support. Tall patients with considerable depression of the lower cartilages caudad to the xiphoid occasionally benefit from a second strut placed anterior to the cartilages and secured to them with heavy absorbable sutures. Although occasional surgeons do not use an internal support strut for patients with PE, we have found that the strut provides complete support to the reconstructed sternum and cartilages, which reduces chest movement with respiratory and physical activity, with resultant reduction of discomfort and enhancement of early ambulation and optimal healing with the desired chest contour.

When large absorbable sutures were placed through the sternum (4 patients) or around the sternum (5 patients) and attached to the anteriorly placed strut, they often broke before adequate stability had been achieved and mild recurrent depression occurred in six patients. A heavy wire around the sternum and strut has provided consistently

optimal results. The strut is placed obliquely across the chest to provide optimal support to the entire sternum, with the left end near the submammary sulcus in women, to facilitate later removal without incising breast tissue. Postoperative chest tube drainage can be avoided in almost all patients with an anterior strut. The relatively mild and short duration of postoperative pain has made it unnecessary to use epidural analgesia, which has reduced operative time, cost, and complications.

Fine wire is placed through the appropriate rib on each side and attached to the ends of the support strut. These wires commonly break within 3 to 4 months, when scar tissue will have grown through the small holes at each end of the strut to provide stability. The strut can then be removed with a single incision over one end, and a second small incision through the vertical scar to remove the large wire around the sternum. Portable C-arm fluoroscopy is helpful to precise identify the tips of the strut.

Optimal postoperative PE management includes encouragement of frequent deep respirations with the assistance of an incentive spirometer. Patients should limit twisting movements of the chest and rapid elevation of the arms overhead for at least 4 to 5 months to minimize torsion of the reconstructed cartilages. Lower extremity exercise (rapid walking, jogging, lifecycle, Stairmaster, etc.) is encouraged within 3 to 4 weeks after the operation, as well as gentle use of light weights to exercise the biceps and deltoid muscles. Chest and abdominal muscles should be used with increasing frequency after 4 weeks. Throwing a ball, pushups, and chin-ups are deferred, and children are excused form routine physical education classes for 5 to 6 months. After sternal bar removal, patients may gradually return to full activities, including body contact sports. Long-term stretching exercises to draw the shoulders posteriorly and improve posture, as well as to avoid hunching over, and frequent deep breathing are encouraged.

Until the past decade, few hospitals had compiled a large surgical experience with most surgeons performing only a few PE repairs each year using a variety of surgical techniques. With the limited individual surgical experience and the many variations of the Ravitch open operative techniques used, the recurrence rate has been relatively high with approximately 15–20% developing moderate-to-severe symptoms and at least half of these patients undergoing reoperation. Factors associated with recurrence include failure to provide adequate support to the sternum and anterior chest with a metal strut, detachment of many perichondrial sheaths from the sternum without adequate reattachment, injury to the perichondrial sheaths while removing the deformed costal cartilages, resection of the costal cartilages in children while the growth plates are active, disrupting the vascularity to the lower sternum, and failure to approximate the pectoralis, and abdominal muscles securely over the cartilaginous repair. Recurrence is more frequent when repair is performed in children younger than aged 10 years.

The 73 patients with recurrent PE deformities who underwent major reconstruction included 62 who had complete resection of deformed cartilages, 24 of whom did not have a sternal support strut. Twenty-two patients from our own experience (2.6%), including four from group IV, underwent reconstruction. The indications for repair in each of these patients were recurrent symptoms, associated with lower sternal and anterior chest depression, with a mean PSI of 4.1. Reconstruction often was more difficult technically than primary PE repair [38]. In patients who had undergone previous complete subperichondrial cartilage resection, it was technically difficult to remove any portion of the regenerated costal cartilages without damaging the surrounding perichondrium. Improvement could not be achieved in two patients.

The overall very good to excellent results with no mortality in 94.2% of the 912 PE patients (97.4% in group IV), using minimal costal cartilage resection, suture attachment of the cartilages to the sternum and ribs after sternal osteotomy, with anterior support strut is effective for all variations of PE, in patients of all ages, has a short operating time, provides a stable early postoperative chest, causes only mild transient pain, and produces better physiologic and cosmetic results than when more extensive open techniques are used. Hospitalization was shorter (mean 2.8 days in groups III and IV) and there was a low rate of complications and low cost, with high frequency of increased exercise tolerance, endurance, and improved cosmetic appearance. It is likely that subperiosteal resection of the entire deformed costal cartilages, as is currently performed in the Ravitch repair and various modifications for both PE and PC deformities may be unnecessary. Preservation of the cartilaginous flexibility of the chest wall during respiration may be physiologically more beneficial than having the frequently rigid regenerated cartilage with calcified or ossified segments, which creates a more rigid cylindrical chest. Additionally, damage to the perichondrial sheaths during costal cartilage resection may result in incomplete regeneration. The described operative technique (group IV) should be clearly distinguished from the more extensive Ravitch technique for PE repair [31].

It is difficult to compare the results in this study accurately with those following the minimally invasive Nuss procedure [28], because each technique has a definite learning curve, and the patient selection is somewhat different. Attention to the fine technical details of each technique is important, with minor variations made for atypical deformities, to obtain optimal results. The Nuss procedure has been most effective for younger children with symmetric PE, whereas the open technique is equally

effective for patients of all ages and with all types of deformities. Because the Nuss support bars remain in place for between 2 and 4 years because of the large amount of force necessary to elevate the sternum and chest wall, very few published reports have provided more than short-term follow-up after bar removal [39]. The recent report by Nuss [40] of 668 patients who had undergone bar removal with 1-year follow-up showed results comparable to those in the present series but with a slightly higher failure rate. It is unlikely that a surgeon will currently perform both operative techniques equally well, and therefore, it may be best for the surgeon to select the operation rather than encouraging the patient to make the decision. The retrospective study of patients during a 4½-year period from two major university medical centers that performed a high volume of PE repair, one using only the Nuss procedure (68 patients) and the other using only open repair (139 patients) is one of the largest comparative studies published thus far [41]. The Nuss procedure has a shorter operating time and small scar; however, the complications were higher, the pain more severe, and the hospitalization longer than with open repair. The short duration of the support strut with the open repair may in part explain the absence of postoperative infections compared with the Nuss bar, which has a low but definite incidence of infections, occasionally requiring early bar removal [42].

It is anticipated that the open repair of PE will be further simplified during the near future to include minimally invasive techniques for costal cartilage resection.

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