

# Twenty-One Years of Experience With Minimally Invasive Repair of Pectus Excavatum by the Nuss Procedure in 1215 Patients

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**Objective:** To review the technical improvements and changes in management that have occurred over 21 years, which have made the minimally invasive repair of pectus excavatum safer and more successful.

**Summary Background Data:** In 1997, we reported our 10-year experience with a new minimally invasive technique for surgical correction of pectus excavatum in 42 children. Since then, we have treated an additional 1173 patients, and in this report, we summarize the technical modifications which have made the repair safer and more successful.

**Methods:** From January 1987 to December 2008, we evaluated 2378 pectus excavatum patients. We established criteria for surgical intervention, and patients with a clinically and objectively severe deformity were offered surgical correction. The objective criteria used for surgical correction included computed tomography (CT) scans of the chest, resting pulmonary function studies (spirometry and/or plethysmography), and a cardiology evaluation which included echocardiogram and electrocardiogram. Surgery was indicated if the patients were symptomatic, had a severe pectus excavatum on a clinical basis and fulfilled two or more of the following: CT index greater than 3.25, evidence of cardiac or pulmonary compression on CT or echocardiogram, mitral valve prolapse, arrhythmia, or restrictive lung disease. Data regarding evaluation, treatment, and follow up have been prospectively recorded since 1994. Surgical repair was performed in 1215 (51%) of 2378 patients evaluated. Of these, 1123 were primary repairs, and 92 were redo operations. Bars have been removed from 854 patients; 790 after primary repair operations, and 64 after redo operations.

**Results:** The mean Haller CT index was  $5.15 \pm 2.32$  (mean  $\pm$ SD). Pulmonary function studies performed in 739 patients showed that FVC, FEV<sub>1</sub>, and FEF<sub>25-75</sub> values were decreased by a mean of 15% below predicted value. Mitral valve prolapse was present in 18% (216) of 1215 patients and arrhythmias in 16% (194). Of patients who underwent surgery, 2.8% (35 patients) had genetically confirmed Marfan syndrome and an additional 17.8% (232 patients) had physical features suggestive of Marfan syndrome. Scoliosis was noted in 28% (340). At primary operation, 1 bar was placed in 69% (775 patients), 2 bars in 30% (338), and 3 bars in 0.4% (4). Complications decreased markedly over 21 years. In primary operation patients, the bar displacement rate requiring surgical repositioning decreased from 12% in the first decade to 1% in the second decade. Allergy to nickel was identified in 2.8% (35 patients) of whom 22 identified preoperatively received a titanium bar, 10 patients were treated successfully with prednisone and 3 required bar removal: 2 were switched to a titanium bar, and 1 required no further treatment. Wound

infection occurred in 1.4% (17 patients), of whom 4 required surgical drainage (0.4% of the total). Hemothorax occurred in 0.6% (8 patients); 4 during the postoperative period and four occurred late. Postoperative pulmonary function testing has shown significant improvement. A good or excellent anatomic surgical outcome was achieved in 95.8% of patients at the time of bar removal. A fair result occurred in 1.4%, poor in 0.8%, and recurrence of sufficient severity to require reoperation occurred in 11 primary surgical patients (1.4%). Five patients (0.6%) had their bars removed elsewhere. In the 752 patients, more than 1 year post bar removal, the mean time from initial operation to last follow up was  $1341 \pm 28$  days (SEM), and time from bar removal to last follow-up is  $854 \pm 51$  days. Age at operation has shifted from a median age of 6 years (range 1–15) in the original report to 14 years (range 1–31). The minimally invasive procedure has been successfully performed in 253 adult patients aged 18 to 31 years of age.

**Conclusions:** The minimally invasive repair of pectus excavatum has been performed safely and effectively in 1215 patients with a 95.8% good to excellent anatomic result in the primary repairs at our institution.

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Since our initial 10-year report of 42 pectus excavatum patients treated without cartilage resection,<sup>1</sup> numerous questions about the safety, efficacy, and physiologic effect<sup>2</sup> of the operation have been raised.<sup>3–7</sup> In this report, we add our experience during a second 10-year timeframe with this minimally invasive operation in an additional 1173 patients, which includes both children and adults, primary and redo operations for a total of 1215 patients over 21 years.

## METHODS

All data regarding evaluation, treatment, and follow-up have been prospectively recorded in a database. Institutional review board scrutiny has been continuous since our initial report in 1997.

From January 1987 to December 2008, we evaluated 2378 patients in our chest wall deformity clinic at the Children's Hospital of The King's Daughters/Eastern Virginia Medical School (Table 1). Patients with a mild or moderate deformity were treated with an exercise and posture program and re-evaluated at 6 to 24 month intervals. Patients with a clinically severe deformity were evaluated by CT scan of the chest, resting pulmonary function studies (spirometry and/or plethysmography), and cardiology evaluation, which included an echocardiogram and electrocardiogram. Surgery was indicated if the patients were symptomatic, had a severe pectus excavatum based on clinical evaluation and fulfilled 2 or more of the following objective criteria: CT index greater than 3.2, evidence of cardiac or pulmonary compression on CT or echocardiogram, mitral valve prolapse, arrhythmia, or restrictive lung disease. Two additional criteria included a history of failed previous repair(s) and significant body image disturbance.<sup>2</sup>

After 2004, a history of nickel or metal allergy and sensitivity to jewelry was sought. If a nickel allergy was suspected or confirmed by testing, then a titanium bar was used.<sup>8</sup>

Surgical repair was performed in 1215 patients. (Table 1). Of these, 1123 underwent a primary (first-time) operation for pectus

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**TABLE 1. Patients Treated 1987–2008**

2378 patients evaluated for chest wall deformity as of December 31, 2008
1215 patients underwent pectus excavatum repair
1123 patients underwent primary operations
92 patients underwent redo operations:
47 failed Nuss procedures
40 failed Ravitch procedures
3 failed Nuss and Ravitch procedures
2 failed Leonard procedures
790 primary patients post bar removal.

2378 patients were evaluated for chest wall deformity between 1987 and 2008 and 51% (1215) of these underwent surgical repair. When only patients from our own region were evaluated, the surgical rate was 33%.

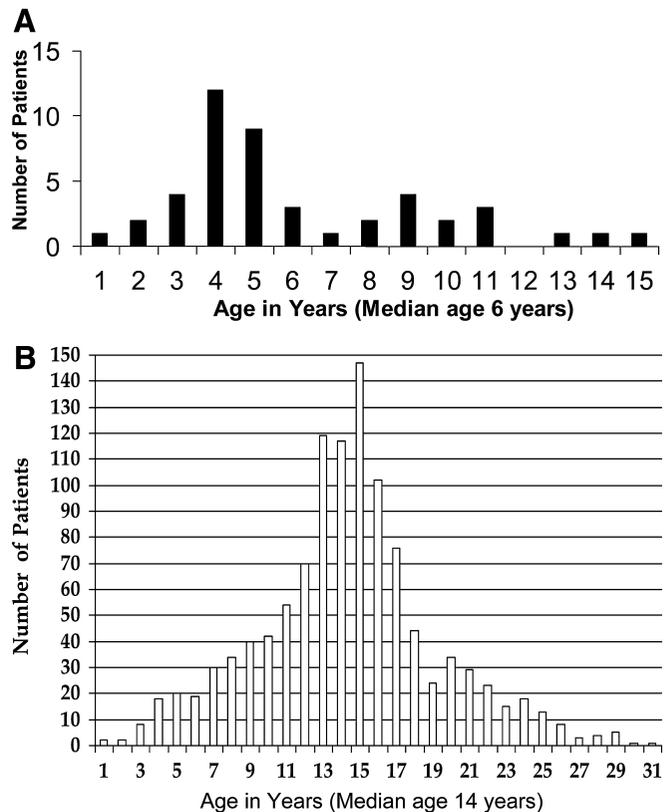
excavatum. These patients are the subject of this report. Ninety-two patients underwent minimally invasive repair following a previous attempt at surgical correction of pectus excavatum by various methods elsewhere; apart from a few general results, they will be reported separately.

Age at surgery was from 1 to 31 years of age. The median age for repair has shifted from a median of 6 years in the first decade to a median of 14 years in the second decade. (Figs. 1A & 1B). This shift has occurred both because of an older age at referral and our preference for repair at the beginning of puberty. However, patients who presented with a severe pectus excavatum and exhibited evidence of cardiac and/or pulmonary compression were repaired at any age, provided they fulfilled the abovementioned criteria for surgical correction, because of the known tendency of pectus excavatum to progress with growth.

During the early learning experience in the 1980s, the bar was sometimes removed between 9 and 18 months after placement, which was too soon, and several patients developed a recurrence. As a result, since 1990, all patients have kept their bar in place for 2 to 4 years depending on the amount of growth. Patients who grew more than 8 inches underwent earlier bar removal.

During the first decade as the operative technique evolved, the incision was moved from the anterior chest wall to 2 small lateral thoracic incisions between the middle and anterior axillary lines and a new, stronger and more streamlined bar was created. In the second decade, new instruments were specially created for the procedure to improve substernal tunnel creation (introducer), to simplify bar rotation (bar flipper), to prevent bar displacement (stabilizer), and 2 new bar benders (1 hand held and 1 table top) were designed to assist with bar bending. Technical aspects of our current approach have been described recently<sup>9</sup> and include:

1. Routine use of unilateral or bilateral thoracoscopy with CO<sub>2</sub> insufflation for better visualization and safety.
2. Multiple techniques for minimizing risk when dissecting between the heart and the sternum in an extremely deep defect, which include:
  - (a) Dissecting the first of 2 transmediastinal tunnels superior to the deepest part of the chest wall depression. After passing the first introducer or tunneling device through the substernal tunnel, it is left in place to keep the sternum elevated while tunneling under the now significantly elevated deepest point of the depression.
  - (b) Off-label use of the chest suction cup to elevate the sternum,<sup>10</sup> and
  - (c) Elevating the sternum manually through an infraxiphoid incision.<sup>11</sup>
3. The use of titanium bars when metal allergy is identified.<sup>8</sup>
4. Choosing a bar length which is 1 inch (2.5 cm) shorter than the measurement from right to left midaxillary line.



**FIGURE 1. A, Age at primary surgery first decade: 1987–1996. B, Age at primary surgery 1987–2008.**

5. More frequent use of a second bar, especially in older patients, in patients who have a diffuse (saucer-type) deformity, a asymmetric deformity, and in patients with connective tissue disorders.
6. Bar stabilization and fixation by attaching a metal stabilizer on the left and placing multiple pericostal PDS sutures around the bar and underlying ribs under thoracoscopic guidance on the right and, if possible, on the left side. We no longer use the absorbable stabilizer introduced in 2004 because inflammatory reactions in some patients caused it to be withdrawn from the market.<sup>9,12–14</sup>

Postoperative pain management has undergone radical revision since the minimally invasive procedure was first developed in the 1980s. After a multicenter study at 10 North American medical centers performing both open and closed techniques reported that both techniques may result in pain scores of 8 on a scale of 10, we completely restructured our pain management program.<sup>15</sup> First, every effort is made to preempt the pain cascade and to allay fear. Patient and parents meet with the anesthesiologist at least 1 day before surgery to discuss epidural analgesia and postoperative pain management and are given a tour of the facility by child life specialists. An oral sedative is prescribed for the night before surgery and midazolam is given 45 minutes before transportation to the operating room. As soon as the epidural is in place, the patient receives fentanyl and bupivacaine via the epidural catheter and a first intravenous dose of ketorolac. To prevent postanesthesia agitation, the patient receives midazolam at the end of surgery, so that emergence from anesthesia is slow and gentle. Ketorolac is administered for 4 days.<sup>16,17</sup> While receiving ketorolac patients are maintained on intravenous fluids and acid-secretion blocking drugs to prevent the potential renal and gastrointestinal side effects of this NSAID.<sup>18</sup> In addition, blood urea

nitrogen and creatinine monitored on day 1 and 3, and if elevated ketorolac is discontinued. On the third postoperative day the PCA infusion is discontinued and the patient is switched to oral pain medications consisting of oxycodone combinations (Lortab or Percocet), muscle relaxants (either Robaxin or diazepam) and ibuprofen. Breakthrough pain is treated with intravenous morphine. Patients are discharged on either the fourth or fifth postoperative day on the same oral pain medications with instructions to wean off them as soon as possible. At this time, we no longer use epidural analgesia.

Deep breathing with the use of an incentive spirometer and ambulation are begun the first postoperative day with the assistance of physical therapists. By discharge from hospital, on day 4 or 5, patients are walking and doing activities of daily life. Patients 12 years old and younger, are encouraged to wean off all their pain meds by 7 to 10 days from the time of surgery. Teenagers and adult patients generally require 2 to 3 weeks. All patients are expected to be off all pain medicine by 4 weeks after operation.

For the first 6 weeks after surgery, patients are encouraged to do deep breathing exercises at least 3 times a day and walk as much as possible. Patients may return to school 2 to 3 weeks after surgery. After 6 weeks, gradual resumption of other physical activity is encouraged. Competitive sports are permitted after 3 months. Heavy contact sports such as boxing, football, and hockey are not permitted when the bar is in place, but are allowed 2 weeks after bar removal.

Postoperative evaluations occur at approximately 1, 6, 24 months, and annually until the bar has been removed. Bars are removed electively between 2 and 4 years after placement and patients are encouraged to continue with deep breathing and aerobic activities after bar removal.

Bar removal is performed under general anesthesia using positive end expiratory pressure (PEEP) to prevent pneumothorax. Our current removal technique includes opening both incisions, mobilizing both bar ends, removing the wire and stabilizer, and straightening the bar with a Malti bender or the Biomet bar flippers.<sup>19</sup> After assuring that the straightened bar moves easily in its fibrous capsule, the bar is removed by slowly pulling it laterally with a bone hook placed through the end hole of the bar. Careful attention is paid to all the monitored vital signs especially the electrocardiogram while mobilizing and extracting the bar.

Every effort is made to examine or contact patients annually until they have stopped growing. Since many have come from a distance, late postoperative follow-up has been challenging. When patients return for checkup both patients and parents are asked to complete a survey regarding their assessment of the results, residual symptoms, their compliance with postoperative exercise instructions, and their willingness to go through the procedure again. (see Appendix I, Supplemental Digital Content 1, online only, available at: <http://links.lww.com/SLA/A79>).

Recurrence is generally evident on physical examination, but is verified radiographically. Pulmonary function is measured during post-operative visits after correction and during visits after bar removal.

## RESULTS

Although patients are referred to our center from other regions because they suffer from very severe deformities, only 51% of the total group of patients evaluated were found to warrant surgery after extensive radiographic and clinical evaluation, based on our objective criteria. When only patients from our own region were evaluated, the surgical rate was even lower at 33%.

CT scanning done as per protocol in neutral chest position, showed a median Haller index of  $5.15 \pm 2.32$  (mean  $\pm$  SD) for the group that underwent surgery.

Pulmonary function studies were obtained in 739 patients prior to operation (Figs. 2A–C). These static (not exercise) studies showed that the median percent predicted value had shifted significantly from 100% in the normal population to 88% for FVC, and 83% for both FEV<sub>1</sub> and FEF<sub>25–75</sub> ( $P < 0.001$ ). In a cohort of 66 patients with a median age of 19 years (range 10–30) who had pulmonary function studies before repair and more than 1 year after bar removal, median FVC improved from 88% to 92% of predicted value ( $P < 0.001$ ); FEV<sub>1</sub> improved from 83% to 88% predicted value ( $P = 0.01$ ); and FEF<sub>25–75</sub> improved from 81% to 87% predicted value ( $P =$  not significant), all by paired  $t$  test. In the normal population, 80% predicted value was chosen to be 2 standard deviations below the mean, and less than 5% of the population has values below “80% predicted.”

Preoperative cardiology evaluation showed dysrhythmia in 16% of our series, including first-degree heart block, right bundle branch block, and Wolff-Parkinson-White syndrome.<sup>2,20</sup> Preoperative echocardiogram showed mitral valve prolapse (MVP) in 18% (216 patients). Forty-four of the patients with preoperative MVP underwent echocardiogram after surgical correction of pectus excavatum, and 20 (44%) had resolution of the MVP.

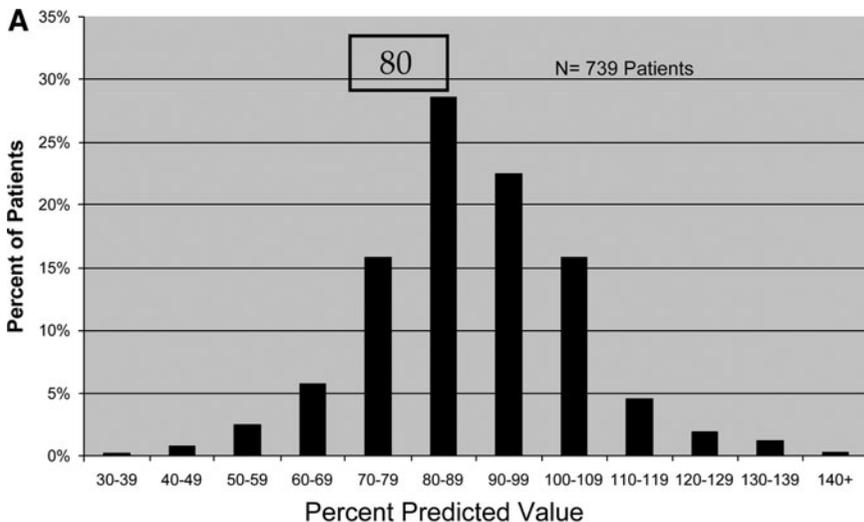
Marfan syndrome was confirmed in 2.8% (35), and an additional 17.8% (232) of the patients had features highly suggestive of Marfan syndrome (“Marfanoid features”) but did not have genetic confirmation of the diagnosis. Marfan patients had a more severe deformity with a median CT index of 8.75 (vs. 5.15 for the group as a whole) and they required 2 bars to correct the deformity in 58% of patients (vs. 29%). Marfan patients had a higher incidence of postoperative infection (6% vs. 1.3%), but, despite the increased severity of the deformity, the patients had a similar outcome: 96% vs 95% good to excellent outcome.<sup>21</sup>

Scoliosis was identified on examination in 28% (340) of the patients. No radiographic evaluation or treatment of scoliosis was undertaken by our clinic. If the patients were prepubertal then the pectus excavatum was usually repaired first, if indicated, and if the patients were post pubertal then the scoliosis was repaired first. The 2 procedures were not performed synchronously.

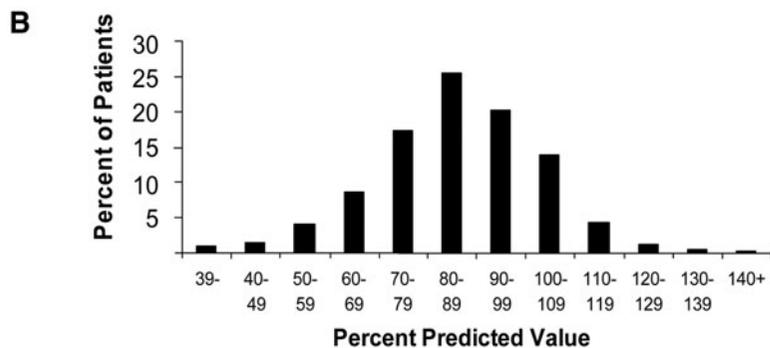
A family history of pectus excavatum was present in 44% (532) of the patients. Genetic evaluation of a subset of these patients (34 families with 2 affected siblings) showed that inheritance occurs by different mechanisms in different kindreds: some families had autosomal dominant transmission; less frequent were autosomal recessive, x-linked, or multifactorial transmission.<sup>22</sup>

In this series of 1123 primary repair patients, 69.3% (775) had 1 bar placed, 30.3% (338) had 2 bars placed and 0.4% (4 patients) had 3 bars placed. As recently as 2001, when Croitoru reviewed our experience up to that time, 87.5% of patients received only 1 bar and 12.5% received 2 bars.<sup>14</sup> The increase in multiple bar placements has occurred especially among older patients, redo patients, Marfan patients, and patients with a diffuse depression. (In patients aged 18–31, the incidence of 2 bars was 51%.) Estimated blood loss was a mean of 10 mL. Median length of stay was 5 days (range, 3–14).

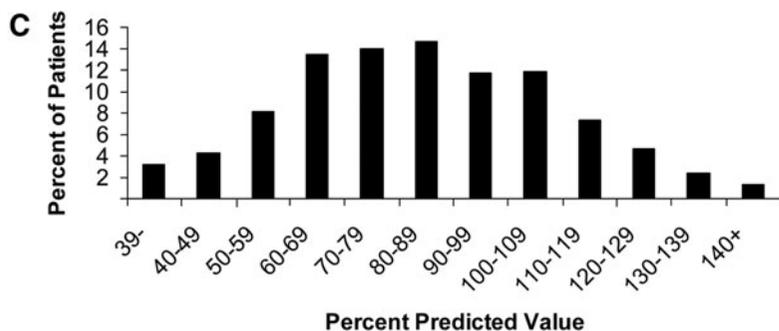
Early and late postoperative complications of primary surgical repairs are summarized in Table 2 and 3. Pneumothoraces with and without chest tube placement are included even though they are an integral part of the procedure and for the most part resolved spontaneously without requiring additional intervention or prolonging hospital stay. Horner syndrome is also included, even though not a true complication, because it is a known reversible side effect of epidural infusion. Hemothorax noted on chest X-ray on the morning after surgery occurred in 4 patients, who underwent thoracoscopy to find the source of the bleeding. Active bleeding had ceased but it appeared to have come from an intercostal vein in 2 patients, from the mediastinum in 1 and from an internal mammary



Pre-operative FVC in 739 patients demonstrating marked Shift to the left with median percent predicted value of 88%.



Pre-operative FEV<sub>1</sub> in 739 patients demonstrated marked shift to the left with median value of 83% of predicted value.



Pre-operative FEF<sub>25%-75%</sub> in 739 patients demonstrated marked shift to the left with median value of 81% of predicted value.

**FIGURE 2.** A, Distribution of FVC in pectus excavatum patients. B, distribution of FEV1 in pectus excavatum patients. C, distribution of FEF 25% to 75% in pectus excavatum patients.

vessel in 1. None required transfusion. Pericarditis occurred in 5 patients, all prior to 2003 at which time more rigorous screening for nickel allergy was instituted. The patients responded to indomethacin and prednisone. One required catheter drainage of the pericardium. Lower extremity paralysis occurred in 1 patient following thoracic epidural catheter placement. Extensive evaluation showed no technical fault. The patient has regained the ability to walk, but still requires bladder catheterization. There were no perioperative or late deaths. Significant early complications were infrequent. Using the Clavien-Dindo Severity Grading System, most of

early primary repair complications fell into Grade I or II, with less than 1 percent grade III, 2 (<1%) grade IV, and no grade V (Clavien, 2009).

Late complications have required a more innovative approach including development of new instruments and included 6% of patients with Grade III Clavien-Dindo Severity Grading System, mostly bar shifts. (Table 3)

Bar displacement was a significant challenge at the beginning but has responded well to new techniques. Bar movement usually presents with sudden onset of pain, and visible subcutaneous

**TABLE 2.** Early Postoperative Complications of Primary Surgical Patients

Pneumothorax with spontaneous resolution	64.7% (n = 727)
Pneumothorax with chest tube	4.0% (n = 45)
Horner's syndrome	15.5% (n = 174)
Drug reaction	3.2% (n = 36)
Suture site infection	1.0% (n = 11)
Pneumonia	0.5% (n = 6)
Hemothorax	0.5% (n = 6)
Pericarditis	0.5% (n = 5)
Pleural effusion (requiring drainage)	0.3% (n = 3)
Death	0%
Cardiac perforation	0%

**TABLE 3.** Late Postoperative Complications

Bar displacements—total	64/1123 (5.7%)
Bar displacements requiring revision	45/1123 (4.0%)
Overcorrection (none required surgery)	41/1123 (3.7%)
Bar allergy (3 required bar removal)	35/1123 (3.1%)
Recurrence	11/1123 (1.0%)
Bar infection—total	6/1123 (0.5%)
Bar infection—required early removal	3/1123 (0.3%)
Hemothorax (post-traumatic)	4/1123 (0.4%)
Lactosorb stabilizer inflammation	4/1123 (0.4%)

protrusion, but there may also be gradual recurrence of the pectus excavatum. A chest x-ray was diagnostic; if the bar had shifted more than 15 degrees it usually required operative repositioning. Bar displacement occurred in 64 of 1123 patients (5.7%), of which 45 (4%) required repositioning. The displacement rate has decreased from 12% in the first decade to 2% in the last 5 years, of whom only half (1%) required repositioning of the bar (Fig. 3.)

Nickel allergy was identified in 35 (2.8%) patients. Since we reported this problem,<sup>8</sup> the complication has been successfully avoided by careful history taking, preoperative skin testing when indicated (Thin-layer Rapid Use Epicutaneous Test patch), and placement of a titanium bar rather than the usual surgical steel bar. Of the 35 patients who were diagnosed with nickel allergy, 22 (2% of the total patients) diagnosed preoperatively received titanium bars. Of the 13 patients who received steel bars and developed allergic reactions, 10 were treated successfully with low dose prednisone until erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) returned to normal. Three required bar removal. Of these, 1 required no further treatment and 2 received replacement titanium bars.

Wound infection was identified in 17 (1.5%) patients. Eleven were superficial infections which responded to antibiotics. They were treated until the ESR, CRP and white blood cell count (WBC) normalized. Six (0.5%) required surgical drainage; of those, 3 (0.27%) required early bar removal.

Late hemothorax occurred in 4 patients. Two were secondary to trauma (1 patient was assaulted and another fell out of an upper bunk). Two other patients presented with spontaneous hemothorax, but no source was found.

An absorbable bar stabilizer, constructed of polyglycolic acid, similar to implants widely used in craniofacial surgery for several years, was introduced in 2004. The device was intended to facilitate bar removal. We (as a high volume center) were asked by Biomet Microfixation to do a pilot study of 10 patients, which was begun in 2004. Around 2005, the absorbable stabilizer was introduced abroad. Subsequent reports of its use were favorable,<sup>23</sup> and 2006, before our pilot study was completed, the FDA gave approval for introduction

**TABLE 4.** Results After Bar Removal Median Follow-Up 854 Days Post Bar Removal

Total no. primary patients	1123
Total number with bar removed	790
Excellent result	674 (85.3%)
Good result	83 (10.5%)
Fair result	11 (1.4%)
Poor result	6 (0.8%)
Recurrence requiring re-do operation	11 (1.4%)
No return	5 (0.6%)

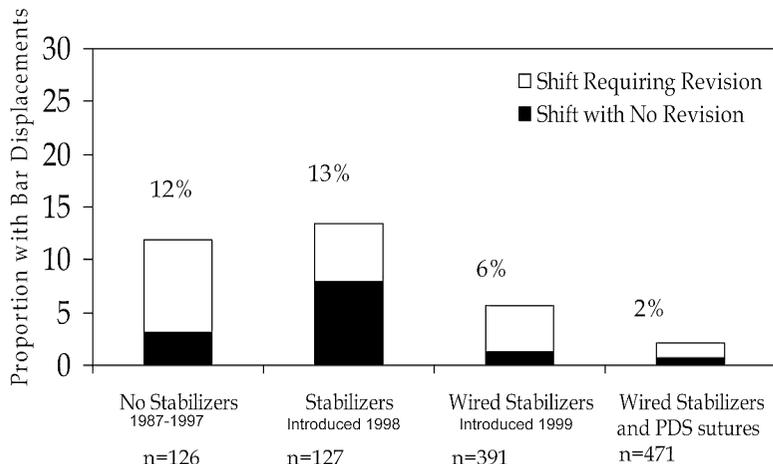
of the absorbable stabilizer into general use in the United States. The 10 patients in the pilot study had no problems during the 3 years that the bars were in place. The original goal of our pilot study was achieved, since at the time of bar removal 3 years after implantation, bar removal was greatly facilitated as there was no scar tissue found at the sites of stabilizer implantation. However, as we began to use the production device, which was slightly different from the unpolished prototype used in the pilot study as it was harder and highly polished, we found that 12% (8-66) of patients developed wound inflammation several months after placement. Most resolved spontaneously but 4 required irrigation and debridement of the wounds and fragments of partially reabsorbed stabilizer material were evacuated. The manufacturer, Biomet Microfixation, voluntarily withdrew the product from the market as soon as these findings were reported to them. We reported this to the American Pediatric Surgical Association<sup>21</sup> at the May 2009 annual meeting, but that group felt that a journal report of the events was unnecessary since the product had already been withdrawn.

The pectus support bars currently remain in situ for 2 to 4 years. In the first decade, during our early experience in the 1980s some patients had their bars removed between 9 and 18 months post-operatively. Those patients had a high recurrence rate and form the majority of the group of 11 who required a redo operation. We initially thought that the recurrence was due to the young age at time of surgery but on further review it has become apparent that although age is an important factor in recurrence, duration of bar placement is even more important (Figs. 4A–C, 5).

There have been few significant complications associated with bar removal, which has been successfully accomplished as an outpatient procedure in 854 patients. Occasional small, insignificant pneumothoraces were noted, which required aspiration in 3 patients. Two patients had small (2–3 mm) residual wire fragments, and 1 patient developed a wound infection which responded to oral antibiotics.

There were 92 patients who presented with failed previous repairs. Of these, 47 were previous Nuss repairs, 40 previous open (Ravitch) repairs, 3 failed open and closed repairs and 2 failed Leonard type repairs (Table 1). Eleven of these patients had their initial surgery at our hospital. Redo patients had significantly more frequent and more serious complications. Two patients who had previous open repairs with very deep and very rigid anterior chest walls (asphyxiating chondrodystrophy) suffered arrhythmic intraoperative cardiac arrest while attempting to elevate their anterior chest walls. They were both resuscitated. Reoperative patients, whether they have undergone Nuss, Ravitch, or Leonard repairs previously, all have pleural and pericardial adhesions as well as cardiac compression. A report on this more complex patient group was published 4 years ago, and will be updated separately.<sup>24</sup>

Apparently unrelated to operation has been occurrence of spontaneous pneumothorax due to blebs in 3 patients months after initial operation.



Improvement in bar displacement rate following introduction of stabilizers and peri-costal sutures. Peri-costal sutures introduced in 2002.

FIGURE 3. Bar displacement of primary surgical patients.

Anatomic results as judged by the operating surgeon at last follow-up for the 790 patients whose bars had been removed for a median follow-up time after bar removal of  $854 \pm 51$  days were as follows: 85.3% had an excellent result, 10.5% good, 1.4% fair, 0.8% poor, 1.4% failed and 0.6% (5 patients) underwent bar removal elsewhere. (See Table 4).

At postoperative office visits, patients and parents were asked to complete a patient satisfaction survey (Appendix I). A total of 798 patients filled out 1420 surveys, and 341 parents filled out 475 surveys (the form was requested at multiple postoperative visits).

Ninety-three percent of patients reported that they were either “very happy” or “happy” with the results. Only 1% of patients were “not at all happy.” Ninety-two percent of parents were “very happy” or “happy”, and 1% of parents were “not at all happy.”

## DISCUSSION

With the introduction of a minimally invasive technique for pectus excavatum repair in 1997, the number of patients presenting for surgical correction increased exponentially. Our series increased from 42 patients in the first 10 years to 1215 patients by the second decade, and other centers have noted similar increases, including those using the open technique.<sup>14</sup> As a result, cardio-pulmonary function studies of patients with pectus excavatum have expanded enormously. We believe that there is now compelling evidence of an adverse effect on the cardiac and respiratory system in severe pectus excavatum. (Figs. 4A–C)<sup>25–29</sup> Historical support for this idea began in 1595, when Bauhinus described a pectus excavatum patient with dyspnea at rest. Sauerbruch, in 1913, performed a successful operation on a young man with a severe pectus excavatum who had been incapacitated by his deformity, but was able to return to work in his father’s watch factory after resection of the chest wall depression.<sup>30</sup> More than 60 years ago, Ravitch and subsequently other surgeons reported paradoxical respiratory chest wall motion in infants with pectus excavatum and a relative inability to exercise.<sup>31</sup> Recently we and others have been able to document that there is perceived inability to exercise in this condition.<sup>15,25</sup>

Sigalet, et al. showed both a significant increase in cardiac stroke volume and cardiac output as well as an increase in pulmonary function studies after repair and after bar removal.<sup>27</sup> MVP occurs in only 1% of the normal pediatric population. However, MVP was identified in 18% of our patients and Shamberger reported a 45% incidence.<sup>32</sup>

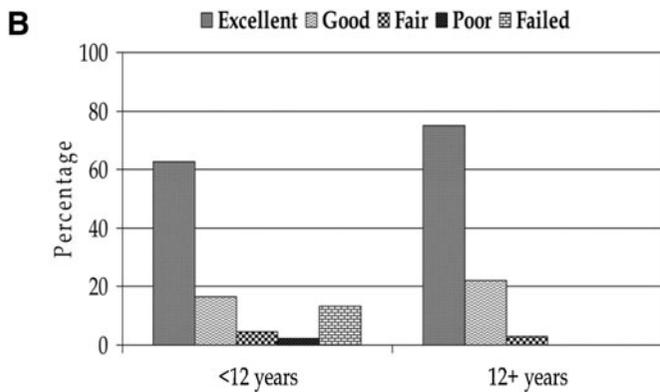
Pectus excavatum patients are otherwise healthy and therefore the only physiologic explanation for decreased spirometry values is the chest wall malformation, since the pulmonary parenchyma and airways of the lung are not generally diseased. Asthma occurs in these children at the same rates as in the general population.<sup>25</sup>

Patient safety remains the most important obligation of any surgeon. All new operations carry not only a “learning curve” but undergo modifications over time. Pioneering an innovative approach without a suitable animal model, we attempted to establish objective criteria for the procedure, maximize the safety of the operation and cope with large numbers of surgeons wishing to adopt it, all without an instruction manual. A total of 120 surgeons observed the operation here in Norfolk during the first 5 years after the technique was first presented at the American Pediatric Surgical Association Annual Meeting in 1997. Some surgeons observed only 1 case, whereas others stayed longer. Subsequently, a significant number of patients came here after having had unsuccessful attempts at minimally invasive correction elsewhere. Most of these patients’ surgeons had not observed the operation here at Children’s Hospital of The King’s Daughters. In response to this problem, we developed a Pectus Excavatum Workshop, held at Eastern Virginia Medical School/Children’s Hospital of The King’s Daughters annually since 2003. More than 300 surgeons from 5 continents have availed themselves of the opportunity to study and observe the procedure. We are delighted to report that the number of patients with failed procedures arriving here has virtually ceased. What is especially gratifying is that the complication rate, both here and as reported by other centers, has fallen dramatically. Surgeons wishing to perform the minimally invasive procedure should be properly trained by taking either a course, or being mentored or proctored by an experienced surgeon.<sup>3,23</sup> We recommend that surgeons adhere to the objective criteria for patient selection.

We, and others, have reported on the complications of the minimally invasive pectus repair in numerous journals. Complications have been discussed at great length, both at medical meetings and in the literature.<sup>33,34</sup> As shown in this series of over a thousand patients, which includes our early learning curve going all the way back to the 1980’s, the complication rate of significant complications is low, and can be reduced even further by applying the approach developed over the 20-year time frame. The commonest significant complication is bar displacement requiring repositioning and that has now been reduced from a peak of 13% to 1% by the introduction



Results of 790 patients who are more than 1 year past bar removal.



\* n=103 Results by age after bar removal during the first decade when patients sometimes had their bars removed between 9 and 18 months which was too soon.



\* n=682 Results by age during the second decade when all patients kept their bars for 2 to 4 years showing that younger patients have almost similar results to older patients.

**FIGURE 4.** A, Results by age after bar removal. B, results by age— January 1987 to December 1998. C, Results by age— January 1999, Present.

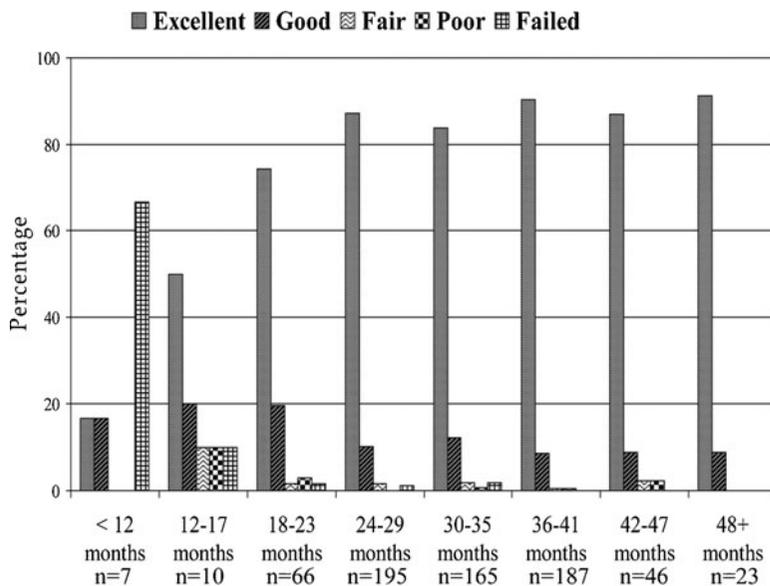
of metallic stabilizers in 1998, the use of pericostal double-thickness 0 PDS (polydioxanone) absorbable suture in 2002, correct length and configuration of the bar and correct placement.<sup>35,14</sup>

**Bar Configuration**

The optimal shape of the supporting bar beneath the sternum is often a point of discussion. We favor a gentle semicircular curve laterally with a 2 to 4 cm flat segment in the center to support the sternum. (Fig. 6). Slight overcorrection of the depression is to be preferred to undercorrection because we believe it minimizes the risk of recurrence and to decreases the risk of buckling of the cartilages. Park et al favor an asymmetrically bent bar for patients with

an asymmetric depression.<sup>36</sup> We have found that asymmetrically bent bars tend to be unstable and therefore we continue to use a symmetrically bent bar even in patients with an asymmetric deformity. Surgeons less practiced in bending the bar may benefit from having it shaped by the manufacturer using computer assisted design/computer assisted manufacturing (CAD/CAM) techniques (Biomet Microfixation, Jacksonville, FL). However, use of (CAD/CAM) technology requires that a CT scan be sent to the manufacturer, and introduces extra expense.

In the initial series, most patients received only 1 bar (in 2001 87.5% received 1 bar and 12.5% received 2 bars), whereas in this series, 30% received 2 bars and, in the older patients (age < 18



**Long-term results by length of time bar kept in-situ showing that removal before 24 months has a higher recurrence rate.**

**FIGURE 5.** Results after bar removal by length of time bar in-situ.



**FIGURE 6.** Optimal bar configuration is demonstrated by the middle bar. Rectangular stabilizer is preferred over the triangular stabilizer.

years), 51% received 2 or more bars. A second bar should usually be added in older patients, taller patients, when the depression is a trench which extends well above the nipples, in those with connective tissue disease, and after failed prior open repair. We think that the surgeon should have a low threshold for placement of a second bar as a second bar distributes the load over a wider area of the chest. In many patients, the correction may appear adequate with a single bar, while the patient is lying in an extended supine position on the operating table, but does not look as good when the patient is in the erect position and resumes his classic pectus posture, (kyphosis of the thoracic spine, forward sloping shoulders, and a protuberant abdomen). We have rarely, if ever, regretted inserting a second bar, but sometimes wished that it had been placed.

Thoracoscopy was introduced in 1998 and there has not been a single cardiac or pulmonary injury in over 1000 primary repair cases. Thoracoscopy is therefore highly recommended. Placing a 5-mm diameter trocar to pass a high-resolution camera into the thorax adds little to the complexity and duration of the operation. The improvement in safety by showing clearly the relation of the deformed sternum and the heart is dramatic.<sup>37</sup> We insert the scope on the right, others prefer the left and some use bilateral thoracoscopy. A 30-degree scope works very well if there is a deep depression. Several techniques for improving visualization by thoracoscopy have been developed elsewhere: bilateral placement of scopes; introducing the scope through the same opening made to put the dissector in the chest, and application of flexible endoscopes.<sup>38-42</sup>

If visualization of the space between the heart and the sternum is poor, techniques to lift the sternum up off the heart should be employed. Incision below the xiphoid to allow a bone hook to pull the sternum anteriorly; sweeping a finger under the sternum, allowing a finger to guide the dissection; or use of the suction cup apparatus developed in Germany all may be helpful.<sup>10</sup>

Patients with a rigid anterior chest wall following previous open pectus repair, and especially if they also suffer from asphyxiating chondrodystrophy are not good candidates for a Nuss operation.

Hemothorax may occur as an acute phenomenon in the first 24 hours after surgery and for that reason we recommend obtaining a chest x-ray on the first morning after surgery. It may also infrequently occur several months later either secondary to trauma or rarely spontaneously and has been described by other centers.<sup>43–45</sup> Despite the fact that we have many patients who compete at a very high level in sports such as soccer, basketball, volleyball, skiing and even football we have had few problems with spontaneous hemothorax. As mentioned previously, there have been only 4 late hemothoraces, 2 of which were due to direct blows to the chest but vigilance is always reasonable and any patient who complains of persistent chest pain and dyspnea should have an urgent chest x-ray taken.

Allergy to nickel, cobalt, or chromium occurs in approximately 13% of the population. Patients with a prior history of metal allergy, those with a family history of metal allergy, those who test positive to nickel, cobalt or some other constituent of stainless steel and patients who suffer from eczema should receive a titanium bar.<sup>8,46</sup> A skin patch test (T.R.U.E.-test) can be applied in the surgeon's office or the patient can be evaluated by an allergist.<sup>47,48</sup> The titanium bar is not very malleable. It is thought that irregularities of the titanium surface will cause tissue ingrowth (as with cementless joint prosthesis). Therefore, it must be shaped by the manufacturer in advance of the surgery utilizing CAD/CAM techniques and is polished at the factory. The stabilizer used with the titanium bar must also be of titanium, and it should be secured to the main bar with a heavy nonabsorbable suture such as Prolene (polypropylene) instead of stainless steel wire. Any modification made to the titanium bar at the operating table should be done without scratching the polished surface.

Thoracic epidural analgesia utilizing bupivacaine and fentanyl is very effective in controlling pain by numbing the chest while resulting in only minor degrees of sedation and has been the mainstay of our postoperative pain management since 1994. Patient controlled analgesia pumps can serve when the epidural route cannot be used. We have had 1 instance of lower extremity paralysis with residual loss of bowel and bladder control following thoracic epidural catheter placement in over a thousand cases. Very extensive radiologic and neurologic evaluation found no fault with the epidural catheter placement and fortunately the patient has regained the ability to walk, but still needs to catheterize the bladder. This unusual complication of epidural analgesia was subsequently reported by others.<sup>49</sup> Pain management in adults is similar to that in children. Since this report was submitted for publication, there has been a second occurrence of lower extremity paralysis after thoracic epidural catheter use. Extensive evaluation disclosed no fault with placement or use. Accordingly, we now utilize patient controlled analgesia (PCA) pain relief.

Activity restriction after surgery is important to prevent bar displacement and consists of restriction from all sports for a minimum of 6 weeks post repair. After 6 weeks, patients may slowly resume noncontact aerobic activities and by 3 months they may resume competitive sports. We have many patients who play high level, competitive sports in high school and college without difficulty. However, if patients start too soon, before the scar tissues has matured, bar displacement may occur. Generally, even very vigorous activities are well tolerated 6 months after operation, except for heavy con-

tact sports such as boxing, American football, ice-hockey, or other similarly bruising activities which are not permitted.

Presently, we favor bar removal no sooner than 24 months after corrective surgery, because during our early learning experience recurrences followed when the bar was removed before 24 months post repair. The date of removal varies between 2 and 4 years depending on surgeon preference, rate of growth (bar should be removed if the patient grows more than 8 inches) and family circumstances. Bar removal 2 years or more after operation has been associated with a very low recurrence rate.

The minimally invasive repair of pectus excavatum has become a standard of care in the decade since it was first published. Several centers worldwide have now reported large experiences with the operation, showing that the procedure can be performed safely and effectively. Several studies have demonstrated improved exercise tolerance and performance including a multicenter study report.<sup>15,27</sup>

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