Minimally invasive repair of pectus excavatum: A novel morphology-tailored, patient-specific approach

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Objective: Minimally invasive repair of pectus excavatum, introduced by Nuss in 1998, has undergone a serious learning curve because of a lack of understanding on morphologies and repair techniques. To summarize the current status of minimally invasive repair of pectus excavatum, we reviewed and appraised our 10-year experience with a novel approach, a morphology-tailored technique, including diverse bar shaping, bar fixation, and techniques for adults.

Methods: We analyzed the data of 1170 consecutive patients with pectus excavatum who underwent minimally invasive repair between August 1999 and September 2008. All pectus repairs were performed by the primary author (H.J.P.) with our modified technique.

Results: The mean age was 10.3 years (range, 16 months to 51 years). There were 331 adult patients (>15 years) (28.3%). A total of 576 patients (49.2%) had bar removal after a mean of 2.5 years (range, 10 days to 7 years). The asymmetry index change (1.10–1.02, $P < .001$) demonstrated post-repair symmetry. Complication rates decreased through the 3 time periods (1999–2002 [$n = 335$]; 2003–2005 [$n = 441$]; 2006–2008 [$n = 394$]) as follows: pneumothorax rate (7.5% vs 4.3% vs 0.8%; $P < .001$) and bar displacement rate (3.8% vs 2.3% vs 0.5%; $P = .002$). Reoperation rate also decreased (4.8% vs 2.5% vs 0.8%; $P = .002$). Satisfaction outcomes were excellent in 92.7%, good in 5.9%, and fair in 1.4% of patients. After bar removal, 3 patients (0.6%) had minor recurrences.

Conclusion: Minimally invasive repair of pectus excavatum based on a novel morphology-tailored, patient-specific approach is effective for quality repair of the full spectrum of pectus excavatum, including asymmetry and adult patients. Continuous technical refinements have significantly decreased the complication rates and postoperative morbidity. (J Thorac Cardiovasc Surg 2010;139:379-86)

The minimally invasive technique for pectus excavatum repair showed high complication and failure rates in initial experiences.¹⁻⁴ Two factors are primarily attributed to this hardship: lack of experience (surgeon factor) and diversity of pectus morphology (patient factor).

Since 1999, we have been in the process of modifying the original Nuss technique of minimally invasive repair of pectus excavatum (MIRPE). This process is categorized in 3 parts: (1) understanding the diversity and complexity of presenting morphologies and conception of a novel morphologic classification; (2) developing repair techniques based on our own theories and experience, which make each repair case-specific; and (3) establishing a secure bar fixation technique according to precise bar displacement mechanisms.

Ultimately, our process of technique modifications has shaped the “multiple target, multiple momentum, terrain contour-matching approach” to fulfill the morphology-tailored, case-specific repair of various types of pectus excavatum.⁵ The aim of this study was to describe the authors’ principles on pectus excavatum repair and demonstrate how the repair techniques have been modified to avoid common pitfalls and hazards.

MATERIAL AND METHODS

We analyzed data from 1170 consecutive pectus excavatum repairs performed between August 1999 and September 2008. The mean patient age was 10.3 years (range, 16 months to 51 years). The male-to-female ratio was 4.1 (941 male; 229 female). There were 331 adult patients (>15 years) (28.3%).

The repair of pectus excavatum was indicated in patients who were physically or psychologically symptomatic. All pectus repairs were performed by the primary author (H.J.P.) with our modified MIRPE technique, as described below. No patient was excluded from MIRPE because of morphology or age criteria, and no patients underwent open repair (Ravitch or sternal turnover procedure) during this period. There were 36 patients who underwent a redo to treat failure of previous repairs in other institutions: 30 Ravitch and 6 Nuss procedures.

We assessed the efficacy of the repair techniques and their surgical outcomes. To verify the quality of repair in asymmetric cases, we used the asymmetry index to evaluate post-repair symmetry.⁶ Postoperative complications were also analyzed. To identify the trends in complications throughout the 10-year period, complication rates for each year were

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Abbreviations and Acronyms

MIRPE = minimally invasive repair of pectus excavatum

plotted and compared. Thereafter, comparisons were made between patient groups divided into 3 time periods: 1999 to 2002, 2003 to 2005, and 2006 to 2008. This study was reviewed and approved by the institutional review board.

Statistical Analysis

Statistical analyses were carried out with the Statistical Package for the Social Sciences (version 10.0, SPSS Inc, Chicago, Ill). Preoperative and postoperative computed tomography indices were compared by paired *t* test, and categoric data were analyzed with a chi-square test.

Surgical Techniques

A patient is placed in a supine position, and both arms are freely hung on overhead slings to avoid arm stretch. A pectus bar shaping is performed on the operating table by the principal surgeon (H.J.P.), which makes it custom-fit to the patient's chest wall morphology. One-centimeter skin incisions are made on both mid-axillary lines. An introducer or the pectus clamp (Biomet Microfixation, Jacksonville, Fla) is passed through the mediastinum with a tactile approach or a specially designed video-scope guided approach. A guide (20F chest tube) followed by the bent bar is passed through. By rotating the pectus bar, the convexity of the bar lifts the depressed chest wall. Both ends of the pectus bar and hinge points are fixed to the adjacent ribs with pericostal sutures. Hemo-vac catheters are inserted in the subcutaneous pockets around the pectus bar or pleural cavities. In adults, teenagers, or patients with severe depressions, to avoid the heart injury and make the procedure easier, the crane system is used to elevate the sternum before passing the introducer (Figure 1).

Morphologic Classification

We formulated a system to classify the morphology of our cases of pectus excavatum, which has been described in a textbook.^{7,8} This system, in which the asymmetric varieties were defined as eccentric, unbalanced, and combined types (Table 1), provides a strategy to select the most appropriate repair technique for each morphologic component, the "morphology tailored approach"⁵ (Figure 2).

The Theories: Multiple Target, Terrain Contour Matching, and Multiple Momentum

Identifying the targets: Multiple target approach. It is common that the target to be corrected is not a single depression, but rather various combinations of multiple depressions or protrusions of the chest wall. Having an eye for recognition of each factor of the deformity has been the first step to a solid repair strategy.⁵

Bar shaping: Terrain contour matching. Once multiple targets are identified in a patient, all these targets must be reflected in the pectus bar shaping strategy to correct every element of the presenting deformity. The term "terrain contour matching" represents matching the bar shape and the external chest wall undulations, in which the pectus bar is bent to a shape exactly duplicating the chest wall morphology. The convexity of the bar works on elevating the depressed portion of the chest wall, whereas concavity (notch) of the bar is created to avoid further elevation of the protruded portion. The terrain contour matching provides a guideline to finalize the bar shape as the exact mirror image of the chest wall topography⁵ (Figure 2).

Repair of complex morphology: Multiple momentum theory.

The positive momentum in the lever system is the main work force for lifting the chest wall depression. The negative momentum refers to a compressing force exerting on the hinge point (pivot). Using the negative momentum is essential for complex morphology repair. Combining the positive and negative momentums in a single bar is the way to correct the "depression-protrusion complex" (type 2C) by elevating the depressed portion and compressing the protruded portion of the chest wall (Figure 2, D). Discovering a role for negative momentum can be the sole solution for relieving the protrusion and achieving an eventual symmetric correction.⁵

Bar Dislocation Mechanism

We have shown that there are 3 mechanisms of bar dislocation. First, "bar flipping" is a return of the bar into its original position before rotation and indicates that the repair is a complete failure. Second, "sliding of the bar" is a lateral sliding toward the left or right side according to asymmetry of the depression. Last, "hinge point disruption" is a strip of intercostal muscle structure at the hinge area that occurs when correcting heavy chest depressions.⁹

Bar Fixation Technique: Multipoint Fixation

Bar fixation techniques have been evolving. Subcutaneous absorbable fixation was abandoned after the initial few cases because of its high failure rate. Thereafter, a lateral stabilizer was routinely implanted in 187 patients, which was basically discontinued in 2001 and saved for only severe asymmetric cases. Finally, we developed a mechanism-based bar fixation technique: multipoint fixation to the corresponding ribs by means of pericostal sutures (wire or absorbable) at the end of the bar plus hinge point(s) (end-hole fixation + hinge point fixation) as a fixation of choice.^{9,10}

For pericostal suture bar fixation, it is often difficult to access the target ribs to be sutured via the skin incision. Therefore, all the necessary pericostal sutures are carried out with a specially designed method, the "through-the-skin suture technique." To keep the incision small, the size only for pectus bar insertion, the entire suturing process is performed outside the lateral skin incisions. First, the targeted rib is palpated and the needle stick is made directly through the overlying skin, passed around the rib, and passed back through the skin. Then, the sutured wires are grabbed via a subcutaneous dissection and pulled out through the incision. The retrieved sutures are passed through the end-hole of the bar and tied. The hinge point fixation suture is also made with the same technique.⁹ This technique makes pericostal suturing easy even to the remote ribs from the incision, while the skin incision remains small (1 cm each side).

The Crane Technique

The "crane technique" involves elevating the depressed sternum before introducer insertion and rotating the bar by means of wire suturing to the bone of the xiphi-lower sternal area end or other area of sternum the lateral side of the sternal body as necessary, and lifting the wire suture along with the sternum by an operating table-mounted retractor system⁹ (Figure 1).

The crane offers 2 main effects. The principal role of the crane is to alleviate the pressure on the bar and hinge points encountered when treating adults (as opposed to children) because of their relatively heavy and stiff chests. The hinge system involving intercostal muscle bundle is not strong enough to sustain the bar for heavy chests. The other is to prevent internal organ injury during the passage of the introducer.

Compound Bar Technique

The compound bar was created to support the heavy chests of adults, where the bar loses its arc while rotating and fails to lift the chest wall and both ends of the bar are separated from the chest wall. The compound bar is a combination of different 2 arcs in a single bar, composed of a more convex central portion and flatter and wider bilateral end portions. The central smaller arc is designed to provide more stiffness to bear the weight and gives more height of the bar, and bilateral large arcs are to fit the width of the chest.⁷

FIGURE 1. Crane technique: elevation of the depressed sternum before mediastinal passage of the introducer and pectus bar. A, An operating table mount crane system elevates the sternum via a wire suture passing through the patient’s sternum. B, Wire suture(s) is (are) delivered through the sternum at the xiphoid process or the lateral side of the sternal body. C, Suture needle strictly passes through the bone between the outer and inner tables of the sternum.

Crest Compression Technique

The crest compression technique uses “negative momentum.” The bar actively compresses protrusions by placing the hinge point exactly on the crest. The compressing pressure is generated by a lever-action when rotating the bar on the crest, which serves as a pivot (Figure 2, D).

Pectus Bar Removal

Pectus bars and wire sutures or stabilizers were removed through the previous incisions. The procedure was carried out under general anesthesia, with 2 or 3 days of hospital admission. Timing for bar removal was 2 years after insertion for pediatric patients (2–3 years for teenagers and 3–4 years for adults).

RESULTS

Repair techniques for each morphologic variation, such as eccentric and unbalanced asymmetries, and for adult patients are listed in Table 1. Multiple bars were required in patients

with multiple targets, for example, in the eccentric long canal type (Grand Canyon type) and in adults with a wide and large chest. Two bars were used in 216 patients (18.5%) (parallel bar technique). None of the patients died as a result of or after the procedure.

Thoracic dimensions changed after repair. Computerized tomography indices decreased: The Haller index changed from 6.05 ± 11.82 to 2.76 ± 0.49 ($P < .001$); the depression index changed from 1.95 ± 1.71 to 1 ($P < .001$); and the asymmetry index for asymmetric type changed from 1.08 ± 0.05 to 1.02 ± 0.02 ($P < .001$).

Complication rates decreased between 1999 and 2008 as follows: total complications (15/51, 29.4% vs 9/185, 4.9%; $P < .001$), pneumothorax (10/51, 19.6% vs 1/185, 0.5%; $P < .001$), and bar displacement (4/51, 7.8% vs 0/185, 0%; $P = .037$). The reoperation rate also decreased (7/51, 13.7%

TABLE 1. Theories support the development of techniques during 10 years of minimally invasive repair of pectus excavatum

Theories	No. of patients	Techniques	No. of patients
1. Morphologic classification			
Symmetric (type 1)	688 (58.8%)		
Asymmetric (type 2)	482 (41.2%)		
Eccentric (type 2A)*	278 (23.8%)	Asymmetric bar technique	471 (40.3%)
Grand Canyon (type 2A3)	161 (13.8%)	Parallel bar technique	216 (18.5%)
Unbalanced (type 2B)†	129 (11.0%)	Seagull bar technique	219 (18.7%)
Combined (type 2C)‡	75 (6.4%)	Crest compression technique	119 (10.2%)
2. Techniques for adults	331 (28.3%)	Compound bar technique	244 (20.9%)
		Crane technique	397 (33.9%)
3. Mechanisms of bar dislocation	24 (2.1%)	Multipoint fixation technique	787 (67.3%)

*The eccentric type refers to the asymmetry resulting from the center of the chest wall depression being off the midline (the center of the sternum). The Grand Canyon type is a long, eccentric, canal-like depression of the ipsilateral chest wall. †The unbalanced type refers to the asymmetry resulting from the slope of each wall of the depression being different. ‡The combined type is a mixed form of eccentric and unbalanced types.

FIGURE 2. Morphology-tailored bar shaping (left column: pre-repair vs right column: post-repair). A, Symmetric bar (bridge shape) for symmetric type (type 1). B, Asymmetric bar for eccentric asymmetry (type 2A). C, Seagull bar for unbalanced type (type 2B): a notch to avoid elevation. D, The crest compression technique for excavatum-carinatum complex: To compress the protruded part of the chest wall, the hinge point is set exactly on the crest (*). By rotation of the bar, the crest was compressed by the negative momentum of the lever action; the “compression-elevation dual action” of the bar. All the results of repair are a symmetric configuration (right).

vs 1/185, 0.5%; $P < .001$). The changes in trends for each complication and reoperation rate are shown in Figure 3. Table 2 depicts the countermeasures for each complication and compares the complication rates among the 3 periods. In comparison of the bar fixation techniques, stabilizers (3.8%, 7/187) showed a higher bar displacement rate than multiple point fixation (1.4%, 10/736) ($P = .036$). Reoperation was performed in 31 patients (2.6%). The reasons for reoperation were bar dislocation in 17 patients (major in 4,

FIGURE 3. Trends of complication and reoperation rate changes. Analysis of 1170 patients from 1999 to 2008 revealed that the multipoint bar fixation technique at point 1 (arrow) and routine hemo-vac drainage at point 2 (arrow) are attributed to major reductions of complications. The secondary peak (*) of the total complication, mainly due to wound seroma and pneumothorax, was resolved by intrapleural and wound drainage with hemo-vac catheter. MPF, Multiple point fixation; HVD, hemo-vac drainage.

minor in 13); progressive contour deterioration in 10 patients; bleeding control in 2 patients; and recurrence after bar removal in 2 patients.

A total of 576 patients (49.2%) underwent pectus bar removal after initial bar placement. The pectus bars were maintained in position for a mean of 2.5 years (range, 10 days to 7 years). Durations according to age groups were a mean of 2.19 years for pediatric patients and 3.7 years for adults. Among them, 18 patients underwent earlier bar removal than initially planned. For early removals, 12 were due to chronic wound seroma or infection, 4 on behalf of the patient's decision, and 2 were due to persistent pain. Patients who underwent premature bar removal (within 1 year for adults and 6 months for children) experienced mild recurrence of the chest wall depression. After the full-term bar removal, 3 patients (0.6%) had minor recurrence, 2 of whom underwent reoperation. Satisfaction outcomes after repair were as follows: excellent in 1085 patients (92.7%), good in 69 patients (5.9%), and fair in 16 patients (1.4%). One patient who had a bar removal after 10 days because of pyogenic wound infection showed failure of repair and was rated as poor (0.001%).

DISCUSSION

With a prevalence of 1 in 1000, pectus excavatum is the most common congenital chest wall anomaly.¹¹ The depressed chest compresses the heart and lungs, causing functional deficits, and elicits emotional problems.

Physical disabilities include repeated upper respiratory infection or pneumonia complicating frequent hospitalization, poor feeding, retarded growth, poor posture, scoliosis, and exercise intolerance. Psychologic problems are obviously

TABLE 2. Postoperative complications and specific measures against each complication (one-to-one correspondence) and changes of complication/reoperation rates among 3 periods

Complication/reoperation	Countermeasure	Complication total (n = 1170)	1999–2002 (n = 335)	2003–2005 (n = 441)	2006–2008 (n = 394)	P value
Pneumothorax	Hemo-vac drainage	52 (4.4%)	25 (7.5%)	19 (4.3%)	3 (0.8%)	<.001
Bar displacement	Multipoint Fixation	25 (2.1%)	13 (3.8%)	10 (2.3%)	2 (0.5%)	.002
Major	Pericostal wire suture	4 (0.3%)	4 (1.2%)	0	0	.034
Minor		21 (1.8%)	9 (2.7%)	10 (2.3%)	2 (0.5%)	.022
Seroma	Hemo-vac drainage	45 (3.8%) (12)*	16 (4.8%)	14 (3.2%)	15 (3.8%)	NS
Pericarditis	Crane technique	13 (1.1%)	13 (3.9%)	0	0	.006
Pleural effusion	Hemo-vac drainage	27 (2.3%)	8 (2.4%)	4 (0.9%)	15 (3.8%)	.020
Hemothorax	Crane technique	13 (1.1%)	3 (0.9%)	7 (1.6%)	3 (0.8%)	NS
Sum		200 (17.1%)	57 (17.0%)	54 (12.2%)	33 (7.5%)	.002
Reoperation		31 (2.6%)	17 (5.1%)	11 (2.5%)	3 (0.8%)	.002

NS, Not significant. *Number of wound infection cases.

loss of self-esteem, avoidance of social activities, and lack of self-confidence. The repair of pectus excavatum has contributed significantly to improve patients’ quality of life.

Patients with pectus excavatum combine various anomalies that sometimes require concomitant surgical corrections.¹² Our patients also revealed a diversity of associated conditions, including genetic diseases, such as Marfan syndrome and Down’s syndrome, congenital diaphragmatic hernia, and congenital lung or heart diseases. Scoliosis is among the most commonly associated comorbidities.

In 1998, a new technique to repair pectus excavatum was introduced by Nuss and colleagues¹¹ and ushered in a new era in surgical treatment of chest deformity. This technique originated from an entirely new concept, using a metal bar to lift the depressed chest wall.

In early experiences of this new procedure, complications of the procedure, such as internal organ injury, bar rotation, and pneumothorax, were unacceptably high and have plagued surgeons adopting this new strategy.^{1–4}

The main reason for failures is that the archetypal Nuss technique encounters limitations in patients with asymmetric morphologies and in older patients with heavier chests who have defective bar fixation. In our series, 41% of pectus excavatum exhibited at least one form of asymmetry or complex-type (depressions and elevations) chest wall morphology. The original technique proposed by Nuss applies symmetrically shaped bars to all types of pectus excavatum regardless of morphologic characteristics. Consequently, many patients failed to achieve symmetric correction. Another problem with Nuss and colleagues’¹¹ technique is that it is not adequate for treatment of adults, who have heavier chests than more typical pediatric patients.^{13,14}

The authors began performing minimally invasive pectus repair in 1999. We also have been through the difficulties in our initial experience and thus have worked to overcome the problems associated with the original Nuss technique. This process began with a meticulous assessment of individual

chest wall morphology and led to the creation of a morphologic classification. On the basis of precise morphologic analysis, targets requiring correction are identified. Then, these targets are incorporated into hinge point selection and the bar bending process, and an asymmetric or complex-shaped bar (eg, seagull, compound) is created matching each patient’s contour⁷ (Figure 2). This is the first and most important step in acquiring post-repair symmetry in asymmetric types.

We have dealt with a variety of asymmetry from the beginning of our series (from the third patient). Some extreme forms of asymmetry, such as the “Grand Canyon type” and “excavatum-carinatum complex,” are challenging to repair. These extreme subsets were of interest, and several techniques and their combinations, including negative momentum, were developed to avoid aggravating or correcting the protruded component of pectus deformity.¹⁵

The majority of the published articles on MIRPE did not offer any insight on asymmetry or generally did not consider those with asymmetry good candidates for MIRPE. However, some surgeons began to adopt asymmetric bar shaping complying to our strategy.¹⁶

The result of our approach was appraised by means of a new computerized tomography index, the asymmetry index, which was developed specifically to evaluate the symmetry of surgical correction.⁶ As postoperative asymmetry index values approach “1,” representing symmetry, our techniques were shown to have achieved symmetric repair.

Bar dislocation is one of the key problems in settling of the new procedure. Bar dislocation results in defective correction or total failure of the procedure. Fixation of the bar to adjacent subcutaneous tissue, as proposed in the Nuss technique, simply does not suffice except in highly selected pediatric patients with less severe and symmetric morphologies. Croitoru and colleagues (the Nuss group) proposed lateral stabilizer as a solution for this serious problem, and they reported that they could reduce the bar dislocation rate with it from 15% to 5%.¹⁷ However, we could not

see any benefit of bar stabilization with stabilizers over our multipoint fixation technique (bar dislocation rate 3.8% with stabilizer vs 1.4% with multipoint fixation); it only made the procedure difficult on insertion and removal. After a meticulous investigation of bar displacement mechanisms, we finally set up the “multiple point pericostal fixations” as a fixation of choice since 2001, instead of routine lateral stabilizers.¹⁰

With our current technique, the multipoint pericostal fixation, the bar displacement rate has decreased further from 3.8% to 0.5% without any major bar dislocations experienced in the most recent 800 patients after 2003. Compared with other fixation techniques demonstrating bar displacement rates ranging between 9% and 3%,^{13,16,17} our technique seems to be simple and reliable. This can be carried out through a tiny, single incision with a through-the-skin suture technique. As shown in our data and other review articles,^{18,19} the multipoint bar fixation technique played a key role in making the MIRPE procedure safer (Figure 3).

Wound seroma, pneumothorax, pericarditis, and pleural effusion are common minor postoperative complications after MIRPE, as demonstrated by previous publications,^{7,10} and have been reviewed in a textbook.²⁰ Wound seroma has proven to be one of the most intractable problems, requiring repeated wound aspirations or resulting in wound dehiscence that often causes prolonged hospital stays and frequent clinic visits or premature bar removal. Routine hemo-vac drainage of wounds resolved this concern and improved recovery, although the occurrence of wound seroma itself did not change throughout the study. Therefore, hemo-vac catheter drainage has been one of the major contributing factors that reduced the postoperative complications (Figure 3).

Postoperative pneumothorax was another common complication. Although primarily transient, prolonged air leakage occasionally made postoperative courses complicated in those who underwent difficult procedures, such as adults or severely asymmetric patients. In those cases, hemo-vac catheter drainage of the pleural space relieves the pneumothorax automatically and enhances the safety of the procedure. In case air leakage from the pleura continued to inflate the hemo-vac drainage bag, the pleural catheter was connected to the underwater-seal drainage and retained until the air leak ceased.

The optimal age for correction with the Nuss technique has not been determined yet, but it is obvious that preschool or elementary school age is suitable for effective repair. In our experience, with careful examination of a wide-ranging age population from 16 months to 51 years, we recommend 3 to 5 years as the best age for repair. Patients of this age have pliable chests, and all the procedures, including the bar removal, will be completed before they attend school. Some 38% of patients in our experience were aged less than 5 years, and there were no particular problems related to this age group.

With greater acceptance of our technique modifications, more adult patients have undergone surgery. However, adult patients are difficult to treat because of their heavy, stiff chests.^{13,14} Many variables, including intercostal muscle stripping (type 3 bar displacement) and insufficient bar strength, caused the procedure to fail in adult patients; thus, we developed unique techniques, the compound bar and the crane technique.⁹ The crane elevates the chest wall before the procedure to allow safe passage of the introducer and to prevent tearing of the intercostal muscles at the hinge points. With proper crane application, the whole procedure, including passing and rotating the bar, is easier and safer. The compound bar is designed to overcome the insufficient strength of the pectus bar for adults and to make tips of the pectus bar adjustable to the chest. These seem to be milestone techniques that make the minimally invasive procedure safe to extend to adult patients.

Postoperative pain has been a limiting factor, especially for adults. In our experience, pain was managed successfully with a fentanyl-based continuous intravenous analgesia (patient-controlled analgesia). We did not use epidural catheter analgesia. Postoperative pain has been further reduced with the crane technique and secure bar fixation by reducing pressure or trauma to the adjacent tissue.

CONCLUSIONS

By following the aforementioned morphology-oriented repair principles and additional troubleshooting techniques, a variety of complex morphologies were repaired successfully. With our most current techniques, the results of asymmetric repairs and treatment of adults compare favorably with those in symmetric, standard subjects. For future facilitation of the minimally invasive repair procedure, we are developing a novel videoscope device that provides continuous visualization of the entire path to guarantee complete safety of the procedure and new bar fixation apparatus for easier and securer bar fixation.

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Discussion

Dr Daniel L. Miller (*Atlanta, Ga*). Dr Park, I applaud you on an outstanding series of minimally invasive pectus repair from your institution. You have taken the standard Nuss procedure to a new level of expertise. I congratulate you on that. The most common complication after a Nuss procedure in an adult is pain. Approximately 50% of patients will experience pain, and some of it can be debilitating. My question for you is, what do you do for the severe discomfort and pain that occur after this procedure? If it does become debilitating, how do you manage the pain with early bar removal, and if you do, have you had an increase in recurrence?

Dr Park. I experienced the same thing in my initial period, but now it's tolerable for most patients. One of the things is the crane technique. The crane elevates the chest wall before we do anything. There should be little trauma to the chest wall. Another important thing is bar fixation. We have to fix the bar stably, and the bar should be comfortably located. So these techniques may improve the results of pain management. Many adult patients can go home within 1 week now. So that should be solved with experience.

Dr Miller. You had 30 patients who underwent a previous Ravitch procedure with a modified morphology-tailored technique that you performed for recurrence. Could you comment on those patients?

Dr Park. That's an excellent question. Those patients are a little bit different cohort from the normal patients with pectus excavatum. They have some irregular chest wall configurations and

deficient ribs. I don't think we can do it perfectly for those patients. What we can do is elevate the sternum further, but there might be more of a chance of recurrence after the bar removal, so there's some concern. I don't have an answer for this now. I'm trying to keep the bar in place for a longer time.

Dr Miller. One last question. In the United States, we have to perform several diagnostic tests before a patient can undergo pectus repair, such as a computed tomography scan for pectus index, an echocardiogram to determine if there's any right ventricular dysfunction, pulmonary function tests to determine restrictive disease, and even sometimes an exercise cardiopulmonary test. What do you do in Korea to evaluate a patient with a pectus defect?

Dr Park. We routinely do computed tomography scans preoperatively and postoperatively. We perform echocardiography in some patients, but it is not that helpful for the patients or surgeons. We perform echocardiography for selected patients. In terms of pulmonary function tests, it is difficult to assess pediatric patients' pulmonary function, so I don't think that is valuable for our surgical approach. My routine examination is computed tomography scans.

Dr Miller. Outstanding series.

Dr Francis Robicsek (*Charlotte, NC*). Why do we call this procedure minimally invasive? You take up to a 3-foot-long metal rod, shove it through both pleural cavities and the mediastinum, a space approximately 1 mm wide between the heart and the sternum; leave it in up to 7 years; watch the patient regularly because of the danger of infection or dislocation of the rod; carry the risk of perforation of every organ in the body but the brain; and then you get the patient back to reoperate, again through two 2-inch incisions. A mesh-supported sternoplasty can be done within 1 hour through a 4-inch-wide incision, after which the patient can ride out into the sunset within 48 hours, forgetting that he ever had a pectus excavatum. That's what I would call minimally invasive! Approximately one third of your patients are adults, and in adults, and even if you do the procedure in young children, you have microfracture of every cartilage in the body, but in adults you have to break the rib to move it. I have seen several of these patients, and our results, I have to admit, are not the best in adults, and we don't operate unless we have a significant anatomic anomaly.

Dr Park. I have not found any evidence that there is fracture with this procedure. We have to find out later. As I answered Dr Miller's question, we have a stable postoperative course for adults too. So this can be one good solution for pectus excavatum in adult patients.

Dr Tomasz Grodzki (*Szczecin, Poland*). I am impressed by your series and the methods of tailoring the bars, but I have a short technical question. We received the bars with the commercially available transverse short metal tips at the ends, which practically eliminate rotation of the bar. You don't use it. What is the reason?

Dr Park. You probably mean the stabilizer.

Dr Grodzki. Yes.

Dr Park. I don't think it eliminates the bar rotation. It has a certain bar rotation rate, probably 5% or 6%. Actually, I routinely used that stabilizer for approximately 2 or 3 years in more than 200 patients, and I compared the results of the fixation techniques, and my final technique of multiple-point fixation is much better than the stabilizers. That is why I abandoned the stabilizers. It has also caused some complications, some wound problems, and it is kind of a big piece of metal, so it's hard to put in, and when we remove the bar, it is difficult to remove. So there is no reason to use that.

Dr Laureano Molins (*Barcelona, Spain*). Congratulations. We have been following your experience, and it is incredible. Your

series is only 30% or 28% adult surgery. We have found that sometimes it's quite difficult to lift up the sternum in adults. We read some years ago the work from Switzerland with the vacuum bell, for use in children and adults. We are using the vacuum bell before surgery, and sometimes it's enough and we don't operate on those patients. Do you have any thoughts of using this vacuum bell, mostly in children?

Dr Park. You mean you use the vacuum bell preoperatively or you just use the vacuum and you don't do the surgery?

Dr Molins. We are trying to operate in fewer patients. We like the Nuss technique, but we try to operate less and less. Effective-

ness and success are so subjective that we found that if there is another nonaggressive procedure to bring the patient satisfaction, it would be better.

Dr Park. I don't have any experience with the vacuum bell, and some magnetic things are under development, but I don't have any experience with that. I think that should be a limited application for selected patients. During the operation, I put the wire stitches to the sternum, and they work well. We can put the stitches anywhere on the sternum. So that kind of thing is helpful to carry out the procedure. I don't have any experience with the vacuum bell.

Dr Molins. I was talking about sparing operations.