The Nuss Procedure for Pectus Excavatum: Evolution of Techniques and Early Results on 322 Patients

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Background. **The Nuss procedure is a minimally invasive technique using a retrosternal bar to repair pectus excavatum. Although its technical simplicity and cosmetic advantages are remarkable, early applications have been limited to children with symmetrical pectus excavatum. We report a large single-institution experience including technical modifications to correct asymmetric configurations and extend the procedure to adult patients.**

Methods. **We retrospectively reviewed 322 consecutive patients who underwent repair of pectus excavatum by the Nuss technique and its modifications between August 1999 and June 2002. Of the patients 251 (78%) were children and 71 (22%) were adults. Precise morphologic characterization of the pectus allowed appropriate shaping of the bar to achieve a symmetric repair.**

Results. **Of the 322, 185 (57%) had symmetric and 137 (43%) had asymmetric pectus excavatum. Within the asymmetric group 71 were eccentric, 47 were unbalanced, and 19 were combined. Modifications to the shape of the bar including asymmetric and seagull bars were developed to deal with these types of asymmetry. A double bar or compound bar technique was used in most of the adults. Multipoint wire fixations to ribs were utilized to prevent bar rotation. Postoperative complications included pneumothorax (n = 24, 7.5%) and bar displacement (n = 11, 3.4%). The bar was removed in 42 patients 2 years after the initial procedure.**

Conclusions. **Precise morphologic classification has led to modifications of the Nuss technique that facilitate correction of virtually all varieties of pectus excavatum including patients with asymmetric varieties and adults.**

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The Ravitch technique and sternal turnover procedures have been the standard techniques for the correction of pectus excavatum [1, 2]. Although the outcome has generally been successful [3] instability of the chest wall due to wide cartilage resection and a large anterior operative scar have been reported [4, 5]. In 1997 a minimally invasive technique for pectus excavatum repair was introduced by Donald Nuss [6]. This procedure remodels the anterior chest wall employing a metal bar without resection of cartilage. This new approach is expected to have better functional and cosmetic outcomes than invasive repairs for symmetrical pectus excavatum. We have been performing the Nuss procedure since 1999 and have modified our techniques to deal with the various types of asymmetry that we encountered. We present the morphologic classification we use, the modified techniques we have developed to deal with each form of asymmetry, and evaluate our early surgical results.

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Patients and Methods

From August 1999 to June 2002, 322 consecutive patients underwent pectus excavatum repair by the Nuss procedure and its modifications. During this period all patients had the minimally invasive procedure regardless of the morphologic type and no patient was turned down. This study is based on a retrospective chart review of these patients.

Morphologic Classification of the Pectus Excavatum

Given the wide spectrum of morphologic variations of the pectus excavatum, we believe it is necessary to employ techniques tailored to each variant for optimal results. One of the authors (H.J.P.) created a morphologic classification system to facilitate decision making.

Figure 1 is a series of computed tomography (CT) scans that illustrate the various subtypes we have identified. The classification begins by sorting the deformities into symmetric ("type 1") and asymmetric ("type 2") varieties. In the symmetric types (1A and 1B in Fig 1), the center of the sternum (C point) and the center of the depression (P point) are colocated. Type 1A is the typical deep symmetrical depression of the lower sternum. Type 1B is the broad, flat type, rather than a deep focal depression.

In asymmetric types the center of the depression is not located in the center of the sternum but is off to one side

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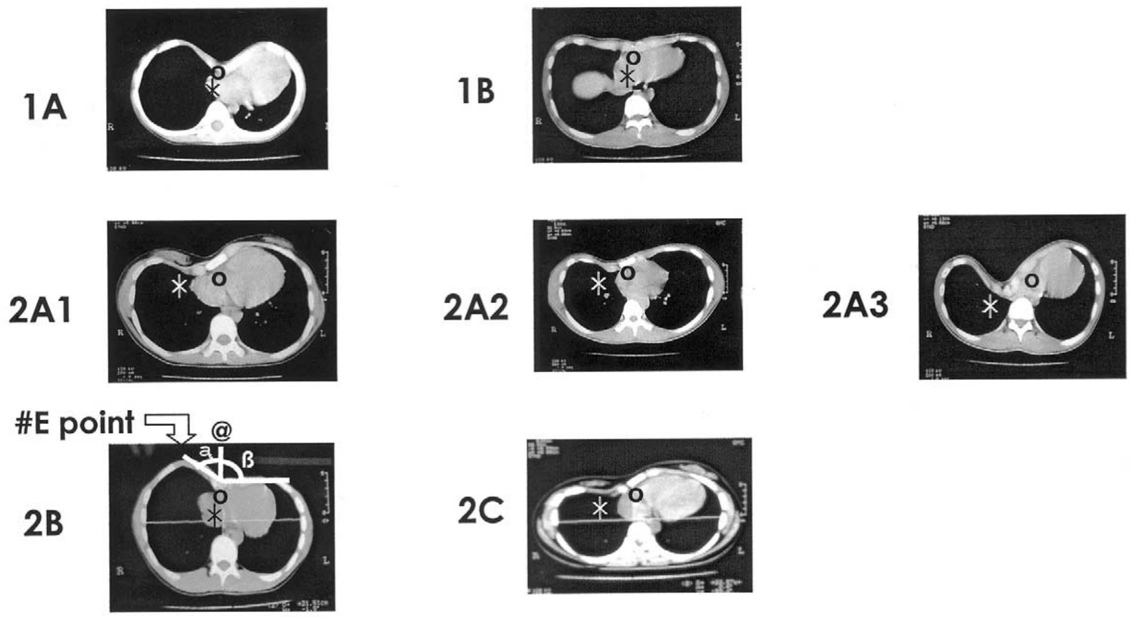

Fig 1. Computed tomography scans of various morphologic types of pectus excavatum. See text for details. O = *center of the sternum (C point);* * = *center of the depression (P point);* #E point = *protruded point of chest wall;* @ = *angles of each chest wall are different ($\alpha < \beta$).*

or the other. We identified three different types of asymmetry. In type 2A, the "eccentric type," the center of the sternum is in the midline but the maximal depression is in the cartilage off to one side. Type 2B, the "unbalanced type," describes the situation where the center of the depression is in the midline but one side of the wall of the depression is more severely depressed than the other. This creates a situation where the angles created by each wall and the vertical axis are different ($\alpha < \beta$). Types 2A and 2B can be further subdivided into focal type (2A1, 2B1) and broad-flat type (2A2, 2B2).

One of the most extreme forms of eccentric varieties is the long canal type ("Grand Canyon" type, 2A3), which is a deep longitudinal groove from the clavicle all the way down to the lower chest. In the Grand Canyon type most of the depression is in the parasternal cartilage not the sternum. Type 2C is a combination of types 2A and 2B.

The CT Index (CTI [transverse diameter/vertical diameter]) [7] was also determined for each patient from the CT scan.

Operative Procedure

The concept of the technique is that a retrosternal metal bar supported at bilateral hinge-points raises the depressed chest wall. Each hinge-point (H point) is an intercostal space located at the crest of the depression on either side and is the point where the bar penetrates the pleural cavity.

C, P, and H points of the deformity are determined and marked on the patient's chest wall. Then small incisions are made bilaterally at the midaxillary line and subcutaneous tunnels to the hinge-points are created. The hinge-point is penetrated with a right angle clamp and then a pectus clamp is passed through at this point into the pleural cavity. The pectus clamp is advanced carefully across the mediastinum under the depressed sternum and emerges through the hinge-point on the other side and finally through the corresponding skin incision. A guide (currently, 32F chest tube) is grasped by the clamp and pulled through the pathway that has been created. This guide is then used to pull through a metal bar (Walter Lorenz Surgical, Jacksonville, FL), which has an appropriate shape for the morphologic type of the deformity (see below). The bar is passed with the convexity facing dorsally, along the curvature of the depressed sternum. Once in place the bar is then rotated 180 degrees around the axis of the hinge points, thus elevating the depression. Both ends of the bar and one hinge-point are then fixed to the ribs by the method described below and the skin incisions closed.

Technical Modifications: Bar Shaping

An appropriate sized bar is selected. Bar size is determined by the length between bilateral midaxillary lines, and the points corresponding to the C and P points are marked on the bar. The bar is then shaped at the operating table to account for the morphologic type of pectus as depicted in Figure 2.

For type 1 (symmetrical) pectuses the bar is initially shaped symmetrically with the C point in the center (Fig 2.1) as originally described by Nuss. However we then bend each side of the bar more than the center to create a bridge shape (Fig 2.2). In our hands this eliminates a problem of the original Nuss shape that often resulted in overcorrection.

For type 2 (asymmetric) pectus we create an asymmet-

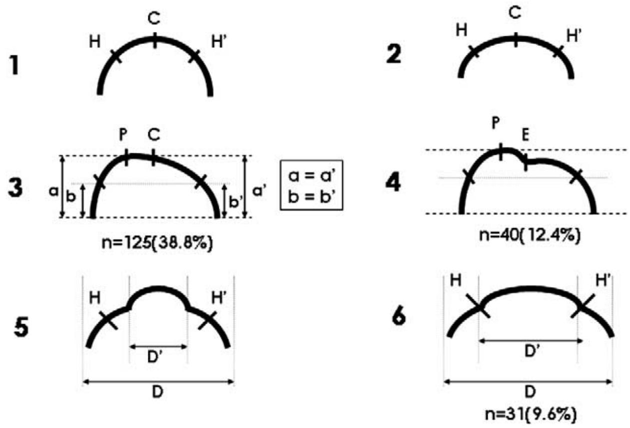

Fig 2. Various shapes of the Nuss bar. (1) Classic. (2) Bridge. (3) Asymmetric. (4) Seagull (5) Hump. (6) Compound. (C = center of the bar; D = diameter of the circle; E = elevated point of the sternum; H = hinge points; P = deepest point of pectus.)

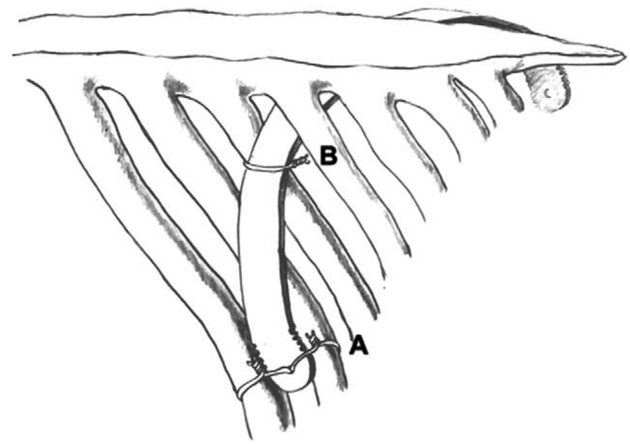

Fig 3. Five-point fixation technique. View of the anterior portion of the right thorax: end hole fixation technique (A) and hinge point fixation on the right (B). See text for details.

ric bar based on the morphology of the pectus. For type 2A pectus we shape a bar that places the maximum convexity of the bar corresponding to point P, the deepest point of the pectus depression (Fig 2.3). For type 2B, the unbalanced pectus, or type 2C, the combined type, a seagull shaped bar was made by creating a notch in the bar corresponding the point of chest protrusion (E point; Fig 2.4).

For adult patients we made additional modifications. To facilitate more central elevation, a "hump-shaped bar" was designed to include a segment of exaggerated central convexity (Fig 2.5). This design provides more resistance to pressure. The stiffness can be further enhanced as necessary to a "compound bar" by placing a smaller central arc between each hinge-point and adjoining at either side by two larger arcs (D > D′; Fig 2.6).

Other Modifications

To place the retrosternal bar exactly at the bottom of the depression, the bar can be placed obliquely using different levels of hinge-points in order to achieve better correction. In cases of the broad or long depressions, two bars are inserted at superior and inferior levels parallel to each other (parallel bar technique).

For larger adults a double bar can be made by affixing a 2-inch smaller supplementary bar to inside of the main bar.

Bar Fixation: The Five-Point Fixation

Fixation of the bar to prevent rotation or displacement is important. Our current technique fixes the bar at five points (Fig 3). At both ends of the bar (Fig 3, A) steel wires encircle the rib above and the rib below, each wire is passing through the end-hole of the bar. A fifth wire is added on the right side at the hinge-point, which encircles the bar and a rib together (Fig 3, B). The pericostal wire sutures are not placed through the lateral incisions rather by piercing the skin over the ribs as it was not possible to place sutures through the incisions. Once placed percutaneously the ends of the pericostal wires can be easily accessed by subcutaneous dissection through the skin incision and knotted to the bar. This maneuver made it possible to do all necessary pericostal sutures through the single tiny incision on each side, even in the parallel bar technique where there are as many as seven or eight pericostal wires.

Results

Patient Population

The age at surgery ranged from 16 months to 46 years with a median of 8 years. Figure 4 depicts the age distribution with 77.9% of the patients being 15 years old or younger. The youngest patient is a 16 month-old boy who showed severe recurrent pneumonia and significant growth retardation. The distribution curve reflects our general recommendation for the timing of correction between 3 to 5 years of age. The male to female ratio was 5.3:1. Ten of the procedures were reoperations for failed previous Ravitch (n = 9) or sternal turnover (n = 1)

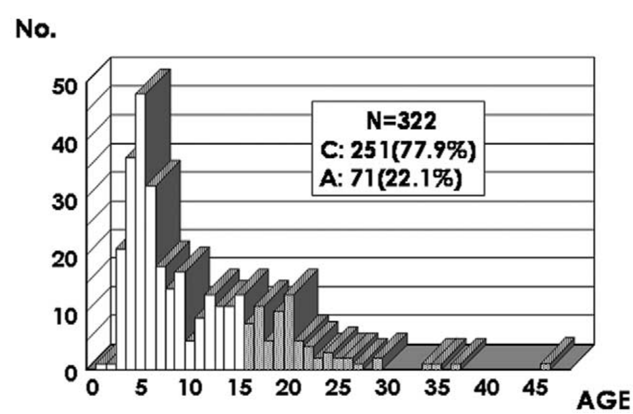

Fig 4. Distribution of age at the time of surgery. (A = number of adults, older than 15 years; C = number of children, 15 years old or younger; N = total number of patients in the series.)

Table 1. Distribution of Patients by Morphologic Type

Morphologic Type	Number	Percent of Total
Type 1: symmetric	185	57.5%
Type 1A: prototype	173	
Type 1B: broad-flat	12	
Type 2: asymmetric	137	42.5%
Type 2A: eccentric	71	
1: focal	33	
2: broad-flat	10	
3: long canal	2	
Type 2B: unbalanced	47	
Type 2C: combined	19	

procedures from elsewhere. Two patients had Poland's syndrome. Table 1 catalogues the numeric distribution of each morphologic type and subtype of pectus.

Computed Tomography Index

For the entire group the mean preoperative CTI was 6.3(range, 2.6 to 250) and decreased to 2.7 (range, 1.8 to 4.5) postoperatively. The mean individual improvement in the CTI was 4.3 (range, 0.3 to 247). The greatest CTI was 250 in a patient of extreme Grand Canyon type. His postrepair CTI has become 3.0; hence the change of CTI was 247.

Distribution of Procedures

Table 2 lists the distribution of the various techniques we have utilized throughout the series as a whole. Over time some techniques have replaced others. It should be noted that the compound bar was only recently introduced in February 2002, which replaced the double bar. Central fixation (Fig 2, 5) was employed for 10 patients who had reoperation for failed previous Ravitch or sternal turn-over procedure.

Outcomes

The results of the repair were excellent in 294 (91.3%), good in 28 (8.7%), and fair in 4 (1.2%). Outcomes in each morphologic type were the symmetric type: excellent 93.5%, good 6.0%, and fair 0.5%; the eccentric type: excellent 83.3%, good 15.6%, and fair 1.1%; and the unbalanced type: excellent 89.4%, good 6.4%, and fair 4.3%.

Table 2. Distribution of Techniques

Technique	Number	Percent of Total
Asymmetric bar	125	38.8
Seagull bar	40	12.4
Parallel bar	42	13.0
Double bar	20	6.2
Compound bar	31	9.6
Oblique bar placement	143	44.4

Table 3. Complications

Complications	Number	Percent of Total
Pneumothorax	24	7.5%
Spontaneous resolution	11	
Needle aspiration	4	
Chest tube	1[a]	
Percutaneous catheter drainage	8	
Bar displacement	11	3.4%
Major (flipped bar)	4	
Minor	7 (3)[b]	
Wound seroma	10	3.1%
Pleural effusion	8 (1)[b]	2.5%
Pericardial effusion (pericarditis)	8 (5)[b]	2.5%
Pneumonia	3	0.9%
Hemothorax	3 (3)[b]	0.9%
Cardiac perforation	1	0.3%
Total complications	61	18.9%
Early complications	49	15.2%
Late complications	12	3.7%

[a] Tension pneumothorax. [b] Late complication.

Complications and Hospital Stay

Table 3 lists 61 complications for an overall complication rate of 18.9%. Of these, 15.2% were early complications (<30 days postoperative) and 3.7% were late. We classify 4.0% of these complications as major including major bar displacement (4), pericarditis (8), and premature bar removal (1).

To address the complication of bar displacement we have changed our stabilization technique. Lateral stabilizers were the method of choice for stabilization in 143 (44.4%) patients operated on before December 2001. Since that time five-point fixation without a stabilizer has been the routine and has been applied in 65 (20.2%) of procedures.

Pericarditis and pericardial effusions have emerged as serious complications in our series. We recommend immediate echocardiography for any febrile patient to facilitate early diagnosis. Conservative management or percutaneous catheter drainage has resolved the acute effusion in all instances but 1 patient developed chronic constrictive pericarditis.

Injury to the heart or other mediastinal structures is rare yet the most tragic complication of the procedure. We had one case of cardiac perforation during the procedure. This was a reoperation for displaced bar, which had been inserted in another hospital 1 year prior. There were likely adhesions in the thorax and the pectus clamp penetrated the right atrium and the right ventricle. The cardiac injury was repaired successfully.

The other complications (14.9%) were minor and self-limited. The most common minor complication was pneumothorax. These were most common in adults or asymmetrical pectus repairs, which were more extensive procedures. In these cases we now electively insert Hemo-Vac catheters (Sewoon Medical Co, Ltd, Hwasung, Kyunggi, South Korea) into the pleural space.

We noted no adverse effect of the Nuss bar outside of those listed complications. Specifically we did not observe somatic outgrowth during the 2 years they were in place. Median hospital stay was 5 days (range, 3 to 22) for children and 7 days (range, 4 to 16) for adults.

Bar Removal

Forty-four patients (13.7%) have had the bar removed; 42 were electively removed as a completion procedure 2 years after the initial operation. However the other two were removed prematurely at 1 year: one because of persisting wound infection and the other at the patient's request. In all 42 patients who have had the bar removed, contour of the initial correction was maintained.

Reoperation

Fourteen patients (4.3%) underwent reoperation. The most common cause was the bar displacement as listed in Table 3. Two other patients had reoperation due to a progressive deterioration of the contour. One of them had Marfan syndrome. One patient was reoperated on for a skin perforation by the stabilizer.

Comment

The Nuss procedure is a new approach to repair of pectus excavatum that offers technical simplicity and cosmetic advantages. Surgeons as well as patients have begun to accept it as the mainstay of surgery for pectus excavatum [8, 11]. However, this technique is still in its developing stages and most surgeons have experienced a learning curve [10, 12–14]. Early in our experience we had technical difficulties trying to apply the original Nuss technique to the wide varieties of pectus morphologies we encountered. This inspired us to develop specific techniques to deal with each morphologic type. We believe this is the key to success.

The central concept of our technique is the recognition of the point to be elevated. That point is the deepest part of the depression (P point). It is this area, not necessarily the center of the sternum (C point), that should be elevated. Selection of hinge-points is another point of importance and we have liberally used oblique positioning when this seemed indicated.

Previous authors have reported difficulty in dealing with asymmetry [8]. In this setting the standard symmetrical bar cannot elevate the depression to the target level without excessive protrusion of the other side. Hence we have tailored asymmetric bars to correct asymmetric types of pectus, causing maximal elevation pressure on the most depressed point in the deformity, wherever it is located.

One of the most challenging morphologies is the unbalanced type of asymmetrical pectus (type 2B). In this setting (Fig 1, insert 2B) a portion of the chest (the E point) is already elevated. The important part of the technique for this variety is to inhibit the further elevation of this area. The function of the seagull shaped bar in combination with the crest compression technique is that the protruded rib (E point) becomes the hinge-point on that side, which tends to depress that point instead of elevating it. In cases of broad or long depression such as the Grand Canyon type, the parallel bar technique was applied.

Use of the Nuss procedure in adults is a relatively new development [15]. The problem has been that the conventional single bar failed to elevate the heavy chest due to loss of the arc and consequently both tips of the bar separated from the lateral chest wall at the hinge points. We developed the double bar technique to overcome this problem and we were initially pleased with the results in our first 20 adults. Subsequently we have developed the compound bar technique and find this modification even more effective. The compound bar is an incorporation of exaggerated convexity in the center of the bar. The concept is a circle with a smaller diameter bearing a heavier load. The compound bar simultaneously resolved the most difficult issues, namely the smaller central arc makes the bar convex enough to elevate the depression and the larger lateral arcs can adjust the width of the bar easily to fit the size of the chest.

There has been a substantial rate of bar displacement with Nuss' original fixation technique [8–10, 12, 16–18]. This occurs more frequently in the severely asymmetric pectus or adult patients. We have observed a variety of mechanisms of bar displacements. Patterns of bar displacement are flipping, lateral sliding, and backward shift (hinge-point breaking). Flipping, the most common, is a rotation of the bar as it pivots on the hinge-point. Lateral sliding of the bar occurs in cases of severe eccentric asymmetry because uneven pressure on each side makes the bar slide down toward the depressed side. Backward shift of the bar occurs when intercostal attachment breaks down because of excessive pressure of the adult chest or uneven pressure of severe asymmetry. Consequently the bar fails to lift the depression to the target level because of posterior movement of the hinge-points.

To prevent the bar displacement, strategies for the fixation should be individualized by anticipating the most likely mechanism of displacement. For the symmetric type we have found the standard five-point fixation is sufficient. For the eccentric types additional support at the depressed side with a stabilizer is necessary in order to block the lateral sliding of the bar. In cases of hinge-point disruption wire reinforcement of the hinge rib should be employed. Other authors have proposed different techniques for the bar fixation [8, 19, 20]; however we have found that our techniques based on morphology seem to be more efficient than others in terms of stability, simplicity, and the ultimate scar. Bar displacement rates in the literature were variable but relatively high. It was 9.2% in a multiinstitutional survey in the United States [8] and other centers showed the rates varying from 4.2% to 19% [9, 10, 12, 18]. Our rates of bar displacement (3.4% overall and 1.2% major displacement) compare quite favorably. While our total complication rate of 18.9% may seem high, most of the complications were self-limited.

Pectus bar removal as a completion procedure is performed after 2 years of bar insertion. The bar removal procedure has generally been uneventful except for frequent wound seromas. One patient required a premature bar removal 1 year after the procedure because of persistent wound infection. Six months after bar removal there has been no change of chest configuration.

We conclude that understanding of the precise morphologic characteristics of pectus excavatum has allowed us to refine and develop techniques to deal with all types of the deformity. That has allowed us to expand the indications of the Nuss procedure to asymmetric types and adult patients.

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DISCUSSION

DR ARTHUR S. PALMER (Chicago, Il): This paper presents a large and impressive series of patients with pectus excavatum deformities corrected by various modifications of the Nuss technique. Doctor Park and his colleagues have developed a new system for the classification of pectus excavatum which is easy to use and includes the variations commonly seen. After classifying these deformities into separate types, they then developed modifications of the Nuss technique for correction of each type.

The Nuss technique is generally described as a minimally invasive technique for repair of pectus excavatum. It is true that it is much less invasive than the classic Ravitch repair; however it is different than most minimally invasive techniques. With most minimally invasive techniques, essentially the same operation is done as in the standard technique. It is simply done through smaller incisions or through ports using scopes and special instrumentations. In the Nuss repair however the goal of correcting the chest wall deformity is accomplished by an entirely different method than that used in the standard technique. Instead of resecting the costal cartilages and doing a sternal osteotomy, the chest wall is remodeled by pressure from the metal bar. If the correction with this technique proves to be durable, the long-term results should be better than the result after the standard open repair. That is because the costal cartilages remain intact and therefore the chest wall should maintain its normal strength and flexibility. In addition the new techniques described today may improve or correct the disparity in the radius of curvature of the ribs on the right and left sides that is seen in the asymmetric types. This aspect of the deformity is not addressed at all with the standard Ravitch repair. To date much emphasis has been put on the minimally invasive aspect of the Nuss technique. A superior long-term result with this technique may eventually prove to be much more important.

The authors are the first to report a large series using modifications of the Nuss technique to extend its applicability. In addition to these creative modifications they have also given us a system for classification that will be important in future reporting.

Finally this is a very promising but nevertheless new technique with a new set of risks and potential complications. We need to apply it cautiously until the long-term results are known, particularly for adults in whom the chest wall is less compliant.

I have only two questions for Dr Park. First, in the patients who had their bar removed, have you found that the adults maintain their correction as well as the pediatric group? Second, your technique of bar fixation with circumferential wires around the ribs is simple and effective. Has it resulted in any symptoms suggesting intercostal nerve entrapment?

I thank Dr Park for allowing me to review his manuscript before the meeting and I congratulate him on this fine work. I also thank the Society for the privilege of discussing this paper.

DR LEIF C. DERNEVIK (Gothenburg, Sweden): I wonder if the correction has only a cosmetic effect or if you can detect some improvement in pulmonary and cardiac function afterwards? And if the purpose is only cosmetic, wouldn't it be more simple to just put a silicone prosthesis under the skin?

DR PARK: Thank you, Dr Palmer, for your kind comments and questions. You have pointed out an important issue regarding results in the adult population. To date there are no published data for adult patients so we simply don't know what is the adequate length of time to maintain the bar in for long-term results. Actually I have not removed the bars from the patients older than 20 years yet so I can only suggest my consideration but I am a bit on the optimistic side.

I have had a few patients who have undergone bar removal earlier than planned because of their persistent wound problems. What I have found was a good maintenance of the correction for up to 1 year of follow-up, even though the bars were removed only 1 year after their initial operation. So now I am considering whether we can remove the bar 2 to 3 years after the operation in selective cases but it remains to be seen.

In response to your second question regarding the neural damage, I agree with you that intercostal nerve damage must be a concern related to the fixation technique. The risk of nerve damage is minimal however. My technique involves muscle tissue rather than simply encircling the ribs. I am happy to report absolutely no incidence of intercostal nerve damage so far.

As for the third question regarding pulmonary or cardiac function improvements and some other cosmetic methods, actually I did not compare my results with other techniques but I believe that this technique is much more physiologic repair than the other method. Particularly just putting some braces or something beneath the skin would not be a good method. I have observed that many patients had a rapid growth after the operation and relief of symptoms like shortness of breath and frequent upper respiratory infections. That would be promising for a further study.