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Multicenter Study of Pectus Excavatum, Final Report: Complications, Static/Exercise Pulmonary Function, and Anatomic Outcomes

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BACKGROUND: A multicenter study of pectus excavatum was described previously. This report presents our final results.

STUDY DESIGN: Patients treated surgically at 11 centers were followed prospectively. Each underwent a preoperative evaluation with CT scan, pulmonary function tests, and body image survey. Data were collected about associated conditions, complications, and perioperative pain. One year after treatment, patients underwent repeat chest CT scan, pulmonary function tests, and body image survey. A subset of 50 underwent exercise pulmonary function testing.

RESULTS: Of 327 patients, 284 underwent Nuss procedure and 43 underwent open procedure without mortality. Of 182 patients with complete follow-up (56%), 18% had late complications, similarly distributed, including substernal bar displacement in 7% and wound infection in 2%. Mean initial CT scan index of 4.4 improved to 3.0 post operation (severe >3.2, normal = 2.5). Computed tomography index improved at the deepest point (xiphoid) and also upper and middle sternum. Pulmonary function tests improved (forced vital capacity from 88% to 93%, forced expiratory volume in 1 second from 87% to 90%, and total lung capacity from 94% to 100% of predicted ($p < 0.001$ for each). VO_2 max during peak exercise increased by 10.1% ($p = 0.015$) and O_2 pulse by 19% ($p = 0.007$) in 20 subjects who completed both pre- and postoperative exercise tests.

CONCLUSIONS: There is significant improvement in lung function at rest and in VO_2 max and O_2 pulse after surgical correction of pectus excavatum, with CT index >3.2. Operative correction significantly reduces CT index and markedly improves the shape of the entire chest, and can be performed safely in a variety of centers. (J Am Coll Surg 2013;217:1080−1089. © 2013 by the American College of Surgeons)

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This trial has been registered at www.clinicaltrials.gov (identifier NCT00236132).

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Abbreviations and Acronyms

FEV_1 = forced expiratory volume in 1 second
FVC = forced vital capacity
HR = heart rate
VE = ventilation
V_{CO_2} = CO_2 production
V_{O_2} = O_2 consumption
WR = work rate

The current prospective, multicenter study examines the safety, efficacy, and complications of surgical repair of pectus excavatum in a group of 327 patients. Previous reports have described the design and methods of the study, reported surveys of body image and perceived ability for physical activity pre and post operation, and described perioperative pain control and postoperative complications for the first 30 days.[1,2] An additional study demonstrated that preoperative lung function decreased with increasing severity of the pectus excavatum as assessed by the chest CT Index.[3]

The current report presents the changes in chest anatomy as assessed by CT scan and the changes in pulmonary function measured by spirometry 1 year after completion of treatment, that is, 1 year after removal of the strut in the open procedure or the bar in the closed procedure. We also present late surgical complications (ie, those occurring more than 30 days after surgery). Finally, we report the results of exercise tests on a subset of subjects before and after surgical correction and conclude with a description of the factors that should be assessed by clinicians in formulating their recommendations about surgical treatment.

Although we had hoped to compare the open procedure as performed by surgeons experienced with that operation with those who practice the minimally invasive Nuss procedure, a randomized trial comparing these procedures was not feasible or practical, as clinician and patient equipoise was lost promptly after the Nuss procedure was introduced in 1997.[1] Patients were scheduled for operative repair by the method of choice for the particular surgeon and family. A failure to enroll similar numbers of open and Nuss operation patients also compromised the ability to compare the 2 operations.

With the exception of the preoperative lung function data, which are summarized so that the magnitude of improvement postoperatively could be evaluated, only data not previously reported are contained in this article. These data include complications of pectus surgery up to 3 years postoperatively in several centers, changes in pulmonary function testing after pectus repair, changes in CT index after operation, and comparisons of exercise test results pre and post operation in a subset of 20 subjects.

METHODS

The details of the design, methods, inclusion and exclusion criteria, and informed consent procedures have been published previously.[1] In brief, 327 patients with pectus excavatum between the ages of 3 and 21 years with a chest CT index[4] $\geq$3.2 were recruited between August 2001 and August 2006. Each patient was followed until 1 year after the last planned surgical intervention (up to 3 years after corrective surgery or August 2009). The cohort of study subjects included patients who underwent the closed procedure or an open procedure for repair of pectus excavatum.

Consent included both parental or guardian written informed consent and assent of the child according to the procedures of the local IRB. Patients were excluded when any of the following applied: pectus carinatum; Poland's syndrome or other complex chest wall anomaly; previous repair of pectus excavatum by any technique; previous thoracic surgery; congenital heart disease; bleeding dyscrasia; history of major anesthetic risk factors, such as malignant hyperthermia; or pregnancy.

Sample size determination, recruitment strategies, web-based computerized data collection, and other methodological considerations are reviewed in our initial report.[1]

The participating centers in the United States and Canada are listed in Appendix 1.

The primary study was funded by a grant from the Children's Health Foundation of the Children's Health System (Children's Hospital of The King's Daughters) of Norfolk, VA, which provided more than 87% of the funding.

A subset of 50 patients underwent exercise pulmonary function studies at several centers but only 20 completed both pre- and postoperative studies. That substudy was underwritten by a grant from Biomet Microfixation, Inc. (formerly known as Walter Lorenz Surgical Inc.), manufacturers of the device used in performing the Nuss procedure only. Data were analyzed and reported by the investigators of the study only.

Cohort management and retention

The Clinical Research Coordinator (CRC) at the coordinating center administered pre- and postoperative body image surveys and 30-day postoperative pain surveys. The methods of assessing pain separately in children 8 to 21 years of age and a parent for the first 30 days post operation have been reported.[2] Patients were followed via phone, mail, or clinical visit at yearly intervals, on or near the anniversary of their surgery, for a period of up to 5 years for complications.

One year after planned treatment was completed (eg, by removal of the support strut for the open group, usually about 6 months after repair; or removal of the pectus bar for the Nuss patients, usually 2 years after insertion), the patients underwent CT scan of the chest and pulmonary function tests. Computed tomography scan cuts were chosen independently by 2 radiologists for each patient. The CTs were read by central review, who were blind as to method of repair.

Complications

Long-term complications for both the Nuss procedure and the open procedure were recorded annually.

Pulmonary studies during rest and exercise

Pulmonary function studies (ie, spirometry, flow-volume curves, and lung volumes) were performed at all centers according to a uniform method before and after operation, and were reviewed by a single pulmonologist who was blind to patient data (Dr Mellins).[5] A progressive exercise study was carried out using a protocol developed by Cooper and colleagues, as reported previously.[6] Of the patients enrolled in this segment of the study, only 20 completed both pre- and postoperative exercise studies. Recognizing from the start the difficulties in obtaining consistency in multicenter exercise testing, the CRC for the study traveled to each center to make every effort to standardize data collection. Unfortunately, the exercise equipment was not identical across study centers. Although each center was able to produce a progressive increase in exercise, the ramp protocols were not identical and some recorded breath by breath data, others recorded 10-second averages. For the 20 patients who had both pre- and postoperative exercise studies, these were always done on the same equipment, facilitating paired analysis and, therefore, we have confined our analyses to these patients. To test the hypothesis that the chest wall deformity in pectus excavatum creates a mechanical inefficiency in both the lungs and the heart, which will be evident as increase in dead-space ventilation (rapid shallow breathing) or decreased cardiac stroke volume during exercise (decreased venous return to the heart), or both, we have used all of the data of the progressive exercise test.[7] The analysis of an increase slope of $\Delta VE/\Delta V_{CO_2}$ (change in ventilation/change in CO_2 production) suggests increased ventilation. In the absence of a change in chemoreceptor set point for Pa_{CO_2}, the most likely explanation for increased ventilation is increased dead-space ventilation.[6] Because differences in arteriovenous difference for oxygen are likely to be small, changes in the slope of $\Delta V_{O_2}/\Delta HR$ (change in O_2 consumption/change in heart rate) are likely to reflect changes in stroke volume.[8] These values were examined because the slopes can be measured throughout the progressive exercise test and they do not depend solely on maximum or peak values and, therefore, were expected to be more robust across studies from multiple sites or centers. By focusing on the slope of the $\Delta VE/\Delta V_{CO_2}$ and $\Delta V_{O_2}/\Delta HR$ during the entire progressive exercise test, the evaluation was expected to be less dependent on the precise calibration at each center. For analysis of the slopes, aggregated individual regressions for pre- and postsurgical $\Delta VE/\Delta V_{CO_2}$, $\Delta V_{O_2}/\Delta HR$, and $\Delta V_{O_2}/\Delta WR$ (work rate) were compared for change using a repeated measures ANOVA. Briefly, after careful calibration, O_2, CO_2, N_2, pulse oximetry, airflows, and work were measured during bicycle exercise. The work load was increased in ramp fashion each minute until volitional exhaustion, which was usually reached within 12 minutes. In addition to the measurement of slope using all of the data of the progressive exercise test, conventional measurements for 20 seconds during maximum work and VO_2 max were also made, including work (watts), VO_2 max, $\Delta VO_2/\Delta WR$, oxygen pulse (VO_2/HR), in the 20 subjects that had measurements made both pre- and postoperatively. Because there were differences in the intervals of time between the preoperative and postoperative studies, we corrected the values made at peak or maximum work by weight.

Quality assurance procedures

Details of quality assurance have been provided previously.[1] In brief, data were reviewed and managed by 4 groups: the study directors to assure consistency of the surgical procedures; a data safety monitoring board (Appendix 2); external study (not financial) audit (Arkios BioDevelopment International); and the investigators at each center. Data were recorded on paper forms and entered on a personal computer into a Welligent database by personnel at each of the 11 clinical centers. Approximately 97% of the forms were reviewed by the CRC. The CRC compared these records with the Welligent database to ensure accuracy.

RESULTS

All 327 subjects enrolled underwent preoperative evaluations, but, on review, some were found to have technically inadequate pulmonary function tests; and not all parents/patients completed every pain survey. The total number of cases for which we have complete studies pre and post operation is noted in Table 1.

Of the 327 patients who enrolled in the initial study and provided complete data, 182 (56%) continued in the study through the 1-year post bar (Nuss) or strut (open) removal, and are included in the current report. Data for demographics and late complications are reported for these 182 patients. Preoperatively, a total

Table 1. Completed Cases by Institution

Institution	Procedure, n Nuss	Open	Total
Children's Hospital of the King's Daughters	76	0	76
Children's Mercy Hospital	27	0	27
All Children's Hospital, Tampa	19	0	19
Children's Hospital Boston	3	17	20
Cincinnati Children's Hospital Medical Center	8	2	10
Hospital for Sick Children, Toronto	0	18	18
Children's Hospital of Wisconsin	8	0	8
Children's Medical Center Dallas	3	0	3
Kapi'olani Medical Center	0	1	1
Total	144	38	182

of 310 completed a full series of technically adequate pulmonary function tests. After bar or strut removal, 159 completed pulmonary function tests and 172 completed CT scans, with 139 completing both. Analyses related to these variables are based on completed cases for the variables of interest.

As with the initial report, the small number of open procedures limits the direct comparisons that can be made between outcomes in these 2 groups of patients.[1] The cohort of patients retained through final follow-up visit is similar demographically to the initial larger pool of participants (Table 2). Patients in the completion cohort demonstrated a higher proportion of connective tissue disorders and were, on average, 9.6 months younger at the time of surgery.

Late complications

Of the 182 patients, 32 experienced at least 1 late complication (more than 30 days postoperatively) (Table 3). Most patients (n = 20) experienced only 1 late complication, with 9 experiencing 2 complications and 3 experiencing 3 complications. The most common complication was bar or strut displacement (7.1% of total). There were no evident differences in complication rates between the operation types.

The 13 patients with bar or strut displacement required reoperation to revise the position of the implanted bar in all but 1 patient. One patient required bar replacement due to bar movement. The 4 wound infections were managed without requiring bar removal. The 4 patients with stabilizer problems (Nuss group) resolved with bar/strut removal at the end of treatment. The 3 patients with pain were managed by altering pain medications and did not require reoperation. The single overcorrection to pectus carinatum occurred in the Nuss group. The mild recurrence 2 years after bar removal in 1 patient occurred in the Nuss group. The single hemothorax occurred during strut removal (open group). Anterior thoracotomy was required for control of internal mammary artery hemorrhage. The hematoma in 1 patient was associated with trauma (from playing tackle football against advice; Nuss group), became infected, and required surgical drainage and early removal of the bar. The single cardiac arrhythmia was transient premature atrial contractions occurring at the time of bar removal (Nuss group). After cardiology evaluation including a normal chest x-ray, electrocardiogram, and echocardiogram, and uneventful overnight observation, the patient was discharged home. The rib erosion was noted on chest x-ray and did not require active management (Nuss group). Rib fracture was noted in 1 patient (Nuss group): on removal, bone/rib had encased the stabilizer/bar and was freed with osteotome and mallet, with approximately 2-cm bone chips removed.

Normalization of the chest wall: computed tomography findings

A substantial normalization of the chest wall was observed across all anatomic locations, with decreases

Table 2. Completed Cases vs Lost Cases

Characteristic	Completed	Lost	Difference
Sex, male, n (%*)	150 (54.0)	128 (46.0)	χ^2 (1) = 2.17, p = 0.14
Ethnicity, n (%*)			χ^2 (1) = 3.15, p = 0.076
White/Caucasian	169 (54.5)	141 (45.5)	
Other	13 (76.5)	8 (23.5)	
Connective tissue disorder (eg, Marfan syndrome), n (%*)	17 (85.0)†	5 (15.0)	χ^2 (1) = 7.27, p = 0.007
Scoliosis, n (%*)	35 (50.7)	34 (49.3)	χ^2 (1) = 0.99, p = 0.32
Asthma, n (%*)	44 (62.0)	27 (38.0)	χ^2 (1) = 1.32, p = 0.25
Presurgical age, y, mean (SD)	13.60 (3.26)†	14.37 (3.50)	t = 2.03, p = 0.043
Presurgical CT index	4.73 (1.38)	4.71 (1.41)	t = 0.14, p = 0.888

*Percentage of cases in category completed or lost.
†Significant difference between completed and lost.

Table 3. Late Complications of Surgical Repair of Pectus Excavatum

Complication	n	% of Total (n = 182)	% of Complications (n = 32)
Bar or strut displacement	13	7.1	40.6
Displacements due to trauma	2	1.1	6.3
Erythema over bar/strut site	5	2.8	15.6
Wound infection	4	2.2	12.5
Stabilizer problems	4	2.2	12.5
Pain	3	1.7	9.4
Hematoma	2	1.1	6.3
Rib erosion or fracture	2	1.1	6.3
Skin rash	2	1.1	6.3
Fever	1	0.6	3.1
Overcorrection creating a pectus carinatum	1	0.6	3.1
Mild recurrence of excavatum 2 years after bar removal	1	0.6	3.1
Cardiac arrhythmia (atrial, premature contractions)	1	0.6	3.1
Strut broken and ingrown into bone	1	0.6	3.1
Pneumonia	1	0.6	3.1
Granulation tissue of bar sites	1	0.6	3.1
Paresthesia	1	0.6	3.1
Depressions and protrusions in chest/asymmetry	1	0.6	3.1
Drug reaction	1	0.6	3.1
Malunion of cartilage	1	0.6	3.1
Persistent drainage of thoracic fluid	1	0.6	3.1
Pneumothorax	1	0.6	3.1
Hemothorax	1	0.6	3.1
Bar required replacement	1	0.6	3.1
Scar revision	1	0.6	3.1
Seroma near incision site	1	0.6	3.1
Poor bar fit due to growth	1	0.6	3.1

Because some patients experienced more than 1 complication, these counts add to more than the total of 32.

in CT index ranging from $\Delta = -0.31$ (sternomanubrial joint) to $\Delta = -1.44$ (xiphoid) Figs. 1 and 2). Changes at all of these locations were statistically significant (paired *t*-test ranged from 5.46 to 14.02; all p values <0.001), with effect sizes ranging from moderate at the sternomanubrial joint to large at the xiphoid.[4] Across all patients in this study, these findings demonstrate that the entire chest wall, not just the most depressed area, showed a returned to a more normal contour after surgical correction. The index did not normalize in all patients, perhaps due to posterior curvature of the osseous component of the ribs laterally, diminishing the anterior-posterior diameter, even when the anterior thorax was flat. Most patients (93.8% [n = 151]) showed decreases in their pectus index, measured at its deepest presurgical location, ranging from 0.05 to 7.71. Of these patients with an improved index, 13.7% (n = 22) showed postsurgical pectus indices in the normal range (<2.5). In a small subset of patients (6.2%; n = 10), the pectus index at the deepest point was actually worse after operation, with a mean increase of 0.30 (SD = 0.21).

Improvement in static pulmonary function

Whole group

Separate paired *t*-tests were used to examine change in pulmonary function from the presurgical to post bar- or stent-removal assessment. Comparisons were made on the basis of percent of predicted to correct for overall growth between the times of the 2 measurements in Table 4. Statistically significant improvements in percent predicted pulmonary function ($p < 0.001$) were observed in percent predicted forced vital capacity (FVC) ($\Delta = +4.8\%$), forced expiratory volume in 1 second (FEV_1) ($\Delta = +3.8\%$), and total lung capacity ($\Delta = +5.9\%$).

Using FVC as a gross indicator of pulmonary function, most pre to post changes were in a positive direction (ie, showed improvement), with 51.2% of patients with preoperative abnormal values moving to within normal

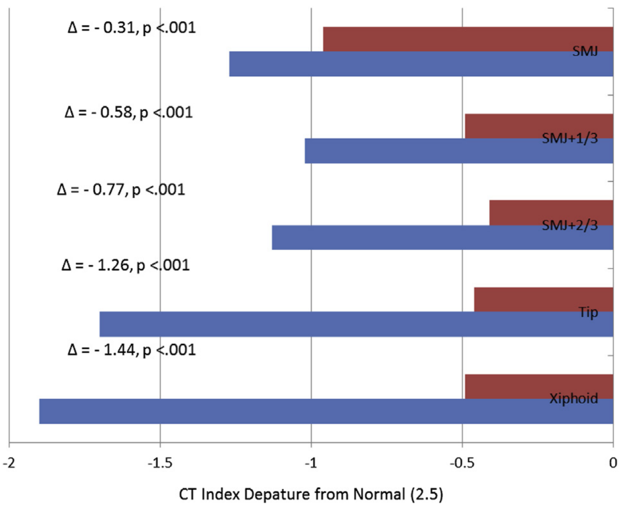

Figure 1. Preoperative and 1 year after bar/strut removal CT Index. Zero on the x-axis represents a normal CT index of 2.5. Bar lengths represent severity of the average chest wall depression at each location, with larger negative numbers indicate larger depressions. SMJ, axial plane passing through the sternomanubrial joint; SMJ + 1/3, axial plane one third the distance between the SMJ and lower end (tip) of the body (gladiolus) of the sternum; SMJ + 2.3, axial plane two thirds of the distance between SMJ and the tip of the body of the sternum; tip, axial plane passing through the lower end of the body of the sternum; xiphoid, axial plane at the lower end of the xiphoid. Red bar, 1-year follow-up; blue bard, preoperative. (From Lawson ML, Barnes-Eley M, Burke BL, et al. Reliability of a standardized protocol to calculate cross-sectional chest area and severity indices to evaluate pectus excavatum. J Pediatr Surg 2006;41:1219–1225, reprinted with permission.)

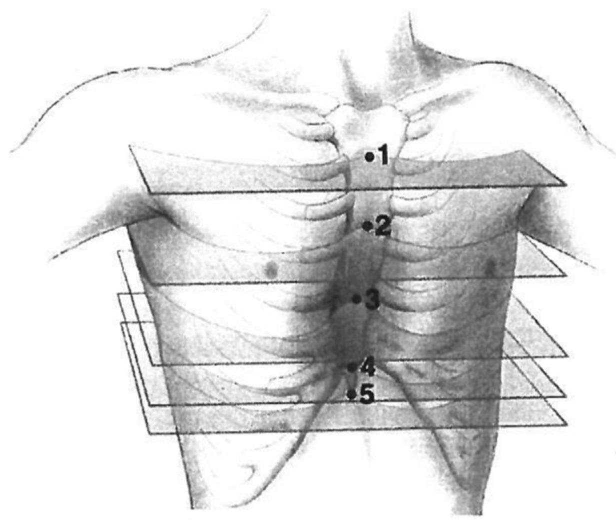

Figure 2. Position 1. Sternomanubrial joint (SMJ); position 2, one third distance from SMJ to tip of body of sternum (SMJ + 1/3); position 3, two thirds distance from SMJ to tip of body (SMJ + 2/3); position 4, tip of body of sternum; position 5, tip of xiphoid. (From Lawson ML, Barnes-Eley M, Burke BL, et al. Reliability of a standardized protocol to calculate cross-sectional chest area and severity indices to evaluate pectus excavatum. J Pediatr Surg 2006;41:1219–1225, reprinted with permission.)

limits vs 7.0% of patients who were within normal limits moving into the abnormal range (χ^2 [1] = 36.26; $p < 0.001$).

Among patients with the most severe preoperative deformities (CT Index >5.2 upper quartile for severity) (n = 40), the improvement in pulmonary function was slightly greater than was observed in the whole group: percent predicted FVC ($\Delta = +6.3\%$), percent predicted FEV_1 ($\Delta = +6.2\%$), and percent predicted total lung capacity ($\Delta = +9.9\%$). A 5% to 10% predicted gain shows that the patient's values improved from ½ to 1 SD of normal subjects.

As expected, FEV_1/FVC ratios, which are low in airway obstruction, were not appreciably different pre to post operation in an operation that primarily affected the chest wall. In so far as lung volume increased postoperatively, that would be expected to increase airway diameter.

Change in pulmonary function during exercise testing

Using all of the data from the progressive exercise testing ($\Delta Ve/\Delta V_{CO_2}$, $\Delta V_{O_2}/\Delta WR$, and $\Delta VO_2/\Delta HR$), aggregated individual regressions for pre- and postsurgical values were compared for change using a repeated measures ANOVA and also correcting for growth (measured via weight change). For the peak workload portions of the progressive exercise test (oxygen pulse, V_{O_2} max, and work), mean values were taken from 20 consecutive 20-second observations during peak workload. These were then analyzed using the same growth-corrected analysis of variance methodology. All but 1 patient had undergone the open procedure (Table 5).

Of the subset of 20 participants in this trial who completed tests of pulmonary function both pre- and postoperatively at peak or maximal exercise, we examined the following:

ΔVE / ΔV_{CO_2}
No statistically significant changes in VE / V_{CO_2} were observed (−2.6%; 95% CI [−7.4%, 2.1%]), with a presurgical ΔVE / ΔV_{CO_2} slightly but not significantly higher (mean 31.1) than at post bar assessment (30.29; $F[1, 18] = 1.374$; $p = 0.256$). Change in ΔVE / ΔV_{CO_2} was not associated with presurgical CT index ($F[1, 18] = 0.043$; $p = 0.839$).

ΔV_{O_2} / ΔHR
No statistically significant changes in ΔV_{O_2} / ΔHR were observed (+6.9%; 95% CI [−5.6%, 19.4%]) with a mean presurgical ΔV_{O_2} / ΔHR slightly but

Table 4. Preoperative to Post Bar/Strut Removal Pulmonary Function Test Findings

	Preoperative, mean (SD)	Post bar or strut removal, mean (SD)	Δ
Pulmonary function test findings, % predicted			
FVC	87.9 (13.0)	92.6 (15.1)	+4.7 ($p < 0.001$, n = 155)
FEV_1	86.6 (13.0)	90.1 (14.7)	+3.8 ($p < 0.001$, n = 153)
FEF_{25-75}	82.8 (21.2)	85.3 (21.8)	+2.5 (p = 0.079, n = 152)
TLC	94.3 (12.8)	100.2 (14.1)	+5.9 ($p < 0.001$, n = 111)
FRC	100.1 (21.3)	113.0 (19.2)	+5.2 (p = 0.025, n = 100)
Ratio			
FEV_1/FVC	0.856 (0.072)	0.848 (0.079)	+0.084 (p = 0.075, n = 153)
RV/TLC	0.267 (0.08)	0.255 (0.07)	−0.012 (p = 0.163, n = 109)

FEF_{25-75}, forced expiratory flow between 25% and 75% exhalation; FEV_1, forced expiratory volume in 1 second; FRC, functional reserve capacity; FVC, forced vital capacity; RV, residual volume; TLC, total lung capacity.

not significantly lower (19.57) than at post bar assessment (20.92; $F[1, 18] = 1.334$; p = 0.263). Change in ΔV_{O_2} / ΔHR was not associated with presurgical CT index ($F[1, 18] = 0.138$; p = 0.715).

ΔV_{O_2} / ΔWR

No statistically significant changes in ΔV_{O_2} / ΔWR were observed (+2.%; 95% CI [−3.1%, 8.4%]), with a presurgical ΔV_{O_2} / ΔWR slightly but not significantly lower (mean 11.30) than at post bar assessment (11.61; $F[1, 18] = 0.954$; p = 0.342). Change in ΔV_{O_2} / ΔWR was not associated with presurgical CT index ($F[1, 18] = 0.450$; p = 0.511).

Oxygen pulse

In postsurgical observations, oxygen pulse values were, on average, 19% higher (95% CI [5.5%, 32.6%]) and 2.58 points higher ($F[1, 19] = 8.68$; p = 0.009). Change in oxygen pulse was negatively associated with presurgical CT index, such that participants with higher presurgical CT indices showed less increase in oxygen pulse, about 2.04 points less increase per 1-unit increase in CT index ($F[1, 18] = 4.72$; p = 0.043).

V_{O_2} max

In postsurgical observations, V_{O_2} max values were, on average, 10.1% higher (95% CI [−4.1%, 15.9%]); 0.32 points higher ($F[1,18] = 1.58$ p = 0.002). Change in V_{O_2} max was not associated with presurgical CT index ($F[1, 18] = 0.20$; p = 0.419).

Work

In postsurgical observations, work values were, on average 11% higher than preoperatively (95% CI [−2.7%, 19.3%]); 19.63 points higher ($F[1, 18] = 7.80$; p = 0.012). Change in work was not associated with presurgical CT index ($F[1, 18] = 0.65$; p = 0.430).

DISCUSSION

This study is prospective and there is no other study of this size that compares the results and complications of pectus excavatum repair. Participating surgeons continued their current practice for treatment. Patients were not directed to one surgeon or another within the study, which encompasses a large geographic area, and there is no reason to believe that the patients who presented to any of the well-known surgeons in this report were different from those at another location.

The CT scan provided a high-resolution assessment of the shape of the chest wall and the anatomic severity of pectus excavatum, and assured that all patients enrolled had a severe chest-wall deformity, ie, a CT index >3.2. Follow-up CT scan demonstrates that most patients had an improvement in this index. This study of a large number of patients also verifies that the overall shape of

Table 5. Preoperative to Post Bar/Strut Removal Exercise Testing

Exercise findings	Preoperative, mean ratio (SD)	Post bar or strut removal, mean ratio (SD)	Δ (Repeat measures *F*)
$\Delta V_E/\Delta V_{CO_2}$	31.11 (4.55)	30.29 (4.40)	−0.82 (p = 0.256)
ΔV_{O_2}/ΔHR	19.57 (5.70)	20.91 (8.17)	+1.34 (p = 0.263)
ΔV_{O_2}/ΔWR	11.30 (1.59)	11.61 (1.85)	−0.30 (p = 0.342)
Oxygen pulse (V_{O_2}/HR)	13.58 (3.53)	16.16 (4.99)	+2.58 (p = 0.009)
VO_2 max (L/min)	3.18 (3.33)	3.50 (3.39)	+0.32 (p = 0.002)
Work (watts)	178.38 (59.38)	198.01 (51.83)	+19.63 (p = 0.012)

HR, heart rate; V_{CO_2}, CO_2 production; VE, ventilation; VO_2, O_2 consumption; WR, work rate.

the chest is improved by repair: not only does the CT index improve at the site of maximum depression, but also at the upper sternum as well. Nakagawa and colleagues also reported improvement in the CT index post correction by the Nuss procedure.[9]

Pulmonary function studies in this multicenter prospective study demonstrated a relatively small decrease in lung function preoperatively with improvement postsurgical correction of approximately 6% to 10%; this is of similar magnitude to results we previously reported in a study confined to Children's Hospital of The King's Daughters patients; note that there was no overlap in the Children's Hospital of The King's Daughters patients in these 2 studies.[5] The improvement in lung function was slightly greater in those with the most severe degrees of depression of the sternum.

The results of the exercise studies postsurgical correction revealed a 10.2% increase in V_{O_2} max and a 19% increase in oxygen pulse, the latter is probably attributable to an increase in stroke volume. Although the mean decrease in pulmonary function preoperatively and the mean improvement postoperatively were statistically significant, the changes were modest in magnitude. However, the large SD indicates that, in some patients, the changes were large; for example, 60% of predicted, and this was graphically demonstrated by plots of the raw data previously.[3] No attempt was made to control for physical training done by participants in the exercise portion of the study. It is possible that improvement might be on that basis.

Increases in oxygen pulse were seen by Sigalet and Haller and their colleagues, although not quite as large as in the current study.[10,11] Malek and colleagues, in a detailed meta-analysis, provided evidence of improved cardiopulmonary function after surgical repair of pectus excavatum.[12] Lesbo and colleagues, using the photoacoustic gas rebreathing techniques for noninvasive determination of cardiopulmonary function during rest, found no difference in cardiac index between control teenagers and those with pectus excavatum, but during exercise found lower cardiac indices in the latter.[13] We measured the oxygen pulse during peak or maximum exercise and have interpreted this increase in O_2 pulse to reflect an increase in stroke volume. Of interest, we did not see an equivalent increase in the slope of $\Delta V_{O_2}/\Delta HR$ using all the data of the exercise test, which we hypothesized would occur if there was an increase in stroke volume. Note that $\Delta V_{O_2}/\Delta HR$ is not the same thing as V_{O_2}/HR. We have no good explanation for this discrepancy unless the increase in O_2 pulse only occurs near peak exercise in these patients with pectus excavatum.

The preoperative functional deficits we and others have reported in pectus excavatum were frequent and fit with the reported symptoms of exercise intolerance or fatigability in almost two thirds of patients.[1] Although the patients with pectus excavatum in this study were all young and healthy and likely had normal lung parenchyma, and the rate of asthma or obstructive disease is the same as the general population, there was a substantial improvement in FVC, FEV_1, forced expiratory flow between 25% and 75% exhalation, and total lung capacity after surgical correction.

By 1 month after surgery, pain had resolved, and different institutional treatment strategies were successful.[1] The most common late complication was displacement of the bar or strut, which occurred in 7.1% of the cases, of which all but 1 required reoperation.

Among the limitations of the study is the lack of a normal control group for the preoperative assessment of the V_{O_2} and O_2 pulse.

Obstacles to the successful conduct of this prospective study have been discussed previously. This report highlights 2 difficulties: retention of subjects long after a successful operation and inter-institutional standardization of exercise pulmonary function testing equipment and procedures. There was little incentive, financial or otherwise, for patients to return for CT scanning or pulmonary function tests 1 year after operation. Future studies should provide a financial or other incentive. Standardization of exercise pulmonary function testing has been an issue in that field.[7]

Regulatory and economic barriers to carry out the work in a rigorous fashion were sufficiently difficult that 16 leading US institutions declined invitations to participate. One result of these difficulties is that we have a disproportionate enrollment of patients from one side of the study, despite heroic efforts on the part of the open operation investigators to recruit centers doing that open procedure.

Among the lessons learned in this study are that a multicenter prospective collaborative study of surgical outcomes is feasible and practical. It is hard to overstate the importance of the coordinating study nurses at each center in carrying out such studies.

Internet-based data collection greatly facilitates the work. Although every communication of data could have been made on paper, the ease of data entry afforded by being able to submit data from any internet-connected computer undoubtedly improved collaboration.

The need for prospective multicenter studies to evaluate new surgical procedures before they become widespread, or to compare them with established procedures, would seem to us to be in society's best interest. Providing external funding by governmental agencies on a competitive basis would facilitate the process.

CONCLUSIONS

Historically, the question has been, does pectus excavatum alter physiology, or does it only represent a purely cosmetic problem? It is clear from a variety of studies, including ours, that the sternal and chest-wall deformity can decrease cardiopulmonary function both at rest and during exercise, that there are practical ways to measure this, and that surgical correction of the anomaly can improve cardiopulmonary function. Although the decrease in lung function preoperatively is more likely to occur when the sternal depression as assessed by chest CT is severe (>3.2), even within the severe group there are some patients whose lung function falls within the normal range when in others it is markedly abnormal.[3] We therefore emphasize the importance of measuring lung function not only during rest but also during exercise to assess the impact of pectus excavatum on cardiorespiratory function and to assess the effect of surgical correction on improving cardiopulmonary function. The recent report of a group of patients older than 50 years of age with lifelong pectus excavatum that only became symptomatic in the 4th or 5th decades of life leads to speculation that even modest decrements in function in an otherwise healthy child or adolescent with pectus excavatum might represent a much larger burden later in life, when there are superimposed alterations accompanying age and illness.[14] Weighing all these factors together with the patient's and parents' eagerness for surgical correction and local surgical experience will continue to be the responsibility of the clinician in helping families decide whether it is indicated to proceed with surgical correction.

APPENDIX 1. PARTICIPANTS IN THE MULTICENTER PECTUS EXCAVATUM OUTCOMES STUDY

Clinical centers

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