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Surgical repair of pectus excavatum relieves right heart chamber compression and improves cardiac output in adult patients—an intraoperative transesophageal echocardiographic study

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Pectus excavatum;
Nuss surgery;
Right heart;
Cardiac output;
Transesophageal echocardiography;
Doppler ultrasound

Abstract

BACKGROUND: Cardiac compression in pectus excavatum (PE) deformity and effect of PE surgery on cardiac function in adults have been debated. We examined the effect of PE correction on right heart size and cardiac output.

METHODS: A retrospective evaluation was performed of 168 adult patients who underwent a modified Nuss PE repair with intraoperative transesophageal echocardiography from 2011 to 2014. Seventeen patients with prior PE repair undergoing bar removal acted as controls.

RESULTS: Mean age was 33.0 years (range, 18 to 71 years). There was an increase in right atrium (15.1%), tricuspid annulus (10.9%), and right ventricular outflow tract (6.1%) size after surgery (all $P < .0001$). Right ventricular cardiac output measured in a subset of 42 patients improved by 38%. No change in chamber size or cardiac output occurred before and after bar removal surgery in the control group.

CONCLUSIONS: Surgical correction of PE deformity caused a significant improvement in right heart chamber size and cardiac output.

Pectus excavatum (PE) is a common malformation of the chest wall with posterior depression of the sternum and adjacent costal cartilages. PE may cause physiologic symptoms and impairment by compression of the right heart chambers and limitation of diastolic filling.[1] The cardiac benefits of surgical correction on PE deformity have been debated.[2–15] Most studies report cardiopulmonary functional performance after surgical repair of PE.[2–14]

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Some studies examined cardiac anatomic changes by transthoracic echocardiography as well as in exercise capacity and demonstrated improvement in both.[2,3,7,10,16,17] Krueger et al[18] showed an improvement in left ventricular ejection fraction and an increase in right heart area by transesophageal echocardiography (TEE) in 17 patients who underwent Ravitch-Shamberger repair. In this study comprising of a large patient cohort, we report preoperative and postoperative effects on cardiac structure and function by intraoperative TEE after surgical correction of PE using Nuss surgical repair. We hypothesized that there would be an increase in right heart inflow and outflow chamber dimensions after PE surgery and this increase would in turn result in an improvement in right heart function as measured by cardiac output.

Methods

A single surgeon (DEJ) performed surgical correction of PE including the techniques of a modified Nuss procedure[19] and a hybrid combined Nuss procedure with partial open cartilage excision/osteotomy, plating, and support bar placement[20,21] during the period of 2011 to 2014. The indications for surgical repair were based on Haller index from computed tomography (CT) or magnetic resonance imaging (MRI; either expiratory when available or inspiratory) of 3.25 or greater,[22] correction index 20% or greater, significant or progressing "unexplained" cardiopulmonary symptoms,[23] and psychosocial symptoms. The Haller index is calculated at axial CT or MRI as the ratio of the widest transverse aspect of the thorax to the minimum anteroposterior aspect of the thorax, measured from the innermost aspect of the anterior chest wall to the anterior cortex of the vertebral body[22]; the correction index is a measure of the percent of chest depression.[24] All types of surgical repair were performed for elevation and/or stabilization of the anterior chest wall. Institutional review board approved the waiver of inform consent and retrospective review of patient's medical charts and studies.

Study Population

Fig. 1 is an algorithm of patient procedures and selection. A total of 273 consecutive adult patients underwent PE repair surgery during this period. Seventy-nine patients who did not have preoperative and/or postoperative TEE images or in whom images were inadequate or technically difficult to make the required measurements were excluded. Twenty-six patients with revision of prior open procedures and other complicating factors including malunion, thoracic dystrophy, and pseudoarthrosis required extensive open reconstructions were also excluded from this analysis. In 42 patients preoperative and postoperative Doppler measurements for right ventricular stroke volume was also performed to evaluate the effect of PE surgery on right heart function. To eliminate the possibility that improvement in chamber dimensions was related to the lifting of the chest from bar insertion and not simply due to anesthesia or chest wall manipulation, we included 17 patients with previous PE repair and placement of stainless steel pectus support bars who underwent scheduled pectus support bar removal with intraoperative TEE before and after bar removal and served as the control group.

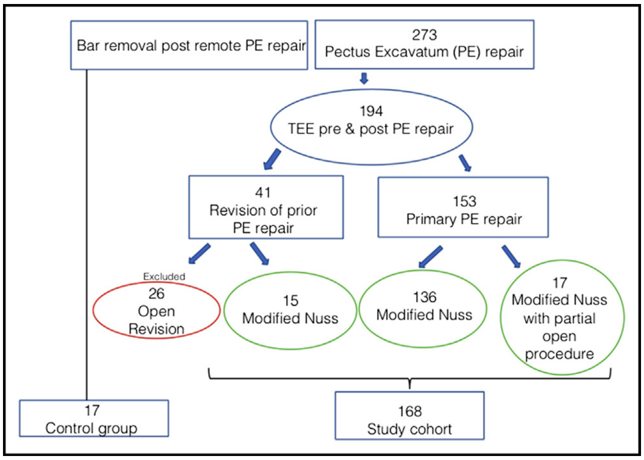

Figure 1 Flow chart of the study cohort and the control group.

Echocardiography

The TEE was performed using a multiplane X7-1 MHz transducer, coupled with a Philips iE33 ultrasound machine (Bothell, Washington). TEEs were performed by expert echo cardiologists using the following image acquisition protocol: (1) right atrium (RA): midesophageal view (ME), transducer angle 0° to 10°, 4-chamber view, RA focused; (2) right ventricle (RV): ME view, transducer angle 0° to 10°, RV focused; (3) right ventricular outflow tract (RVOT): ME view, transducer angle 20° to 70°; (4) pulsed wave (PW) Doppler RVOT velocity time integral (VTI): transgastric long axis view RVOT; and (5) pulmonic annulus diameter (midsystolic): ME view, transducer angle 20° to 70 ° or deep transgastric view.

Image Analysis

Image analysis was performed retrospectively. Digital Imaging and Communication images stored at our institutional server the time of TEE study were retrieved onto a PROSOLV image viewer (FUJIFILM, Indianpolis, IN USA). Measurements were made using electronic caliper function in the PROSOLV image viewer. No calibration of 2-dimensional or Doppler images was required. For 2-dimensional images, an average of 2 measurements and for Doppler, an average of 3 measurements was used. All patients were in normal sinus rhythm, and all had normal left and RV systolic function. All measurements were performed by a single experienced observer.

Right Heart Chamber Size

The following right heart chamber dimensions were measured in presurgery and postsurgery TEE images in comparable views: RA size (end-systole), tricuspid annulus size (end-systole), and RVOT (end-diastole and end-systole). All measurements were based on American Society of Echocardiography guidelines 2013[25] as follows:

1. RA size: This was measured as the maximal mediolateral RA diameter in ME 4-chamber view, with the transducer angle 0° to 10°, at end-systole.
2. Tricuspid annulus size: This was measured at end-systole as the distance from medial to lateral tricuspid annulus in the same view as the RA measurement.
3. RVOT size: This was measured in ME aortic valve short axis view, transducer angle 20° to 70°. The narrowest diameter .5 to 1.0 cm under pulmonary valve at end-diastole and the largest diameter .5 to 1.0 cm under pulmonary valve, at end-systole were measured.

Right Heart Function

Right heart function was assessed by PW Doppler of the RVOT in the deep transgastric view with as parallel Doppler alignment to RVOT as possible. VTI and pulmonic annulus diameter were used to measure RV stroke volume and cardiac output presurgery and postsurgery. RV stroke volume was calculated as $.25 \times 3.14 \times VTI_{RVOT} \times (\text{RVOT diameter})^2$ and RV cardiac output as: (RV stroke volume) $\times$ (heart rate). Heart rate and blood pressure were measured presurgery and postsurgery. Heart rate was recorded from the echo PW Doppler images for VTI measurement, and blood pressure was acquired from the presurgery and postsurgery anesthesia records.

Interobserver Variability

Nine patients were selected for repeat measurement of tricuspid annulus size. Observer 2 was kept blind to the results of observer 1 before the final analysis.

Statistical Data Analysis

Prism 5.0 (GraphPad Software, Inc., San Diego, CA) was used for statistical analysis. All values are in mean ± standard deviation. The paired, 2-tailed Student *t* test was used for comparison between presurgery and postsurgery measurements for each structural parameter and for variables used for calculating cardiac output. For reproducibility test, the measurements of 2 observers were analyzed by paired, 2-tailed Student test. Bland-Altman plot and linear regression analysis were applied to analyze the consistency of interobserver measurements.

Results

Study cohort—modified Nuss surgery

Evaluation of 168 patients undergoing Nuss PE repair was performed. Mean age was 33.0 years (range, 18 to 71 years); 74.2% of patients were males; mean Haller index was 5.7 ± 3.1 (range, 2.3 to 24.3); 153 patients (91.1%) underwent primary PE repair; and 15 patients (9.9%) underwent revision of prior failed or recurrent PE.

Open revision group

Of the 26 patients who received open revision, there were 21 males (80.8%) and 5 female (19.2%); the mean age was 34.3 years (range, 19 to 54 years). Mean Haller index was 4.7 (range, 2.8 to 14.7).

Control group

In the control group, there were 17 patients (13 males [76.5%] and 4 females [23.5%]); the mean age was 35.2 years (range, 21 to 53 years). The average time between the 1st pectus repair surgery and the bar removal surgery was 3 years.

The Correlation of Haller Index, Right Heart Chamber Size, and Cardiac Function Before Surgical Correction

No significant correlation was found when comparing Haller index with preoperative RV stroke volume (P = .6274) and preoperative RV cardiac output (P = .3361). However, significant correlation was present between preopertative RA size (r = .32, P = .0485) and tricuspid annulus size (r = .33, P = .0467) with RV stroke volume.

Effect of Pectus Repair Surgery on Right Heart Chamber Size

A significant increase in right heart chamber dimensions occurred postsurgery in patients (Fig. 2A–D). Improvement in RA, tricuspid annulus end systolic, RVOT end diastolic, and end systolic dimension was 15.1%, 10.9%, 6.1%, and 6.1%, respectively (all $P < .0001$ vs preoperative dimensions). No significant change in right heart chamber size occurred before and after bar removal surgery in the control group. The data are shown in Fig. 2. Fig. 3A–D demonstrates the compression of right heart chambers by TEE in a patient with PE and the improvement after surgical repair. Compared to preoperative values, open revision group had nonsignificant change in RA end systolic (5.8%), tricuspid annulus

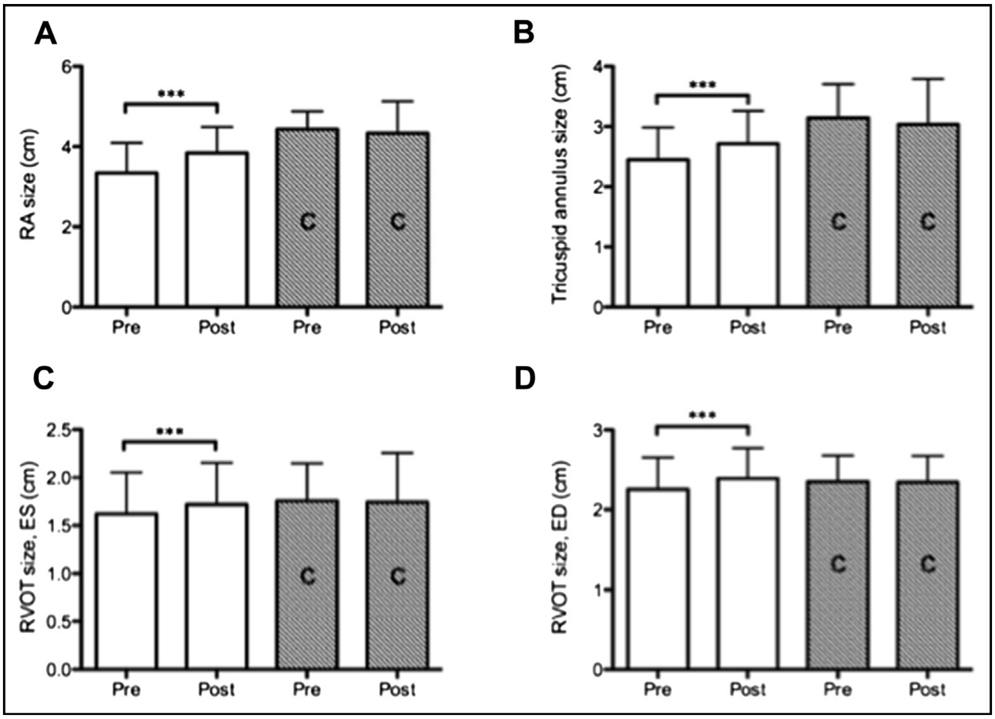

Figure 2 Right heart chamber size in 168 patients who underwent Nuss PE repair in comparison to the 17 controls (labeled C) who underwent bar removal. Right atrial size (A), tricuspid annular size (B) and RVOT systolic (C) and diastolic size (D) all increased post PE surgery. Improved right heart dimensions are shown postsurgical repair vs baseline (***$P < .0001$ in paired, Student t test). All parameters significantly improved in the Nuss surgical PE repair group, without any significant change in the control group. Data are mean ± SD. ED = end diastolic; ES = end systolic; RA = right atrium; RVOT = right ventricular outflow tract; SD = standard deviation.

end systolic (6.1%), RVOT end diastolic (−2.0%), and end systolic dimensions (2.8%), all P values are nonsignificant.

Effect of Pectus Repair Surgery on Right Heart Function

In 42 patients in Doppler assessment of RV, cardiac output was performed. Compared to preoperative values, RVOT VTI increased 16.2% (from 12.5 ± 2.7 to 14.6 ± 4.3 cm, $P = .0035$; Fig. 4A) in patients. Calculated RV stroke volume increased 33.6% (from 47.2 ± 17.9 to 63.1±18.1 mL, $P < .0001$; Fig. 4B), and RV cardiac output increased 38.3% after surgery (3.3 ± 1.2 to 4.5 ± 1.3 L/min, $P < .0001$; Fig. 4C). There was no significant change in heart rate (71.3 ± 12.7 to 71.6 ± 13.6 bpm, P = nonsignificant) or systolic blood pressure (121.9 ± 18.0 to 122.3 ± 17.0 mm Hg, P = nonsignificant) after surgery. In contrast, open revision group did not show any significant change in RVOT VTI (2.0%, P = nonsignificant) or stroke volume. In the control group, no significant difference occurred in the right heart function as shown in Fig. 4.

Interobserver Reproducibility

The mean of tricuspid annulus size measurements (n = 9) of the 2 observers was 2.37 ± .39 vs 2.27 ± .36 cm (P = nonsignificant). There were a strong linear correlation ($r = .89$, $P = .0012$) and close agreement between the 2 observers with mean bias of .092 cm.

Comments

The cardiopulmonary indications of PE repair have remained controversial due to contradictory results of studies. Jayaramakrishnan et al[26] reviewed data from 22 studies evaluating postsurgical repair cardiopulmonary performance. Among the 22 studies, only 6 directly evaluated cardiac structure or function by transthoracic echocardiography[4,7,10,15–17] as preoperative TEE was considered to be subject to the limitation of abnormal anatomy of PE. In the 6 studies, the earliest postoperative evaluation was at 3 months after surgery, which showed a significant improvement in the stroke volume.[10] Hu et al[7] reported improvement of left ventricular (LV) stroke volume and ejection fraction; however, growth may also contribute to the improvement because of the young age at surgical intervention (mean age, 4.6 years, range, 2.5 to 16 years). Coln et al[15] recorded the relief of heart compression, but did not report changes in cardiac measurements. In a 17-patient study, Krueger et al[18] showed significant improvement in RV size and LV ejection fraction using intraoperative TEE after Ravitch-Shamberger surgery performed between 1999 and 2004. No other study has used TEE to evaluate the immediate effects of PE repair on right heart compression. Gursu et al[27] reviewed 25

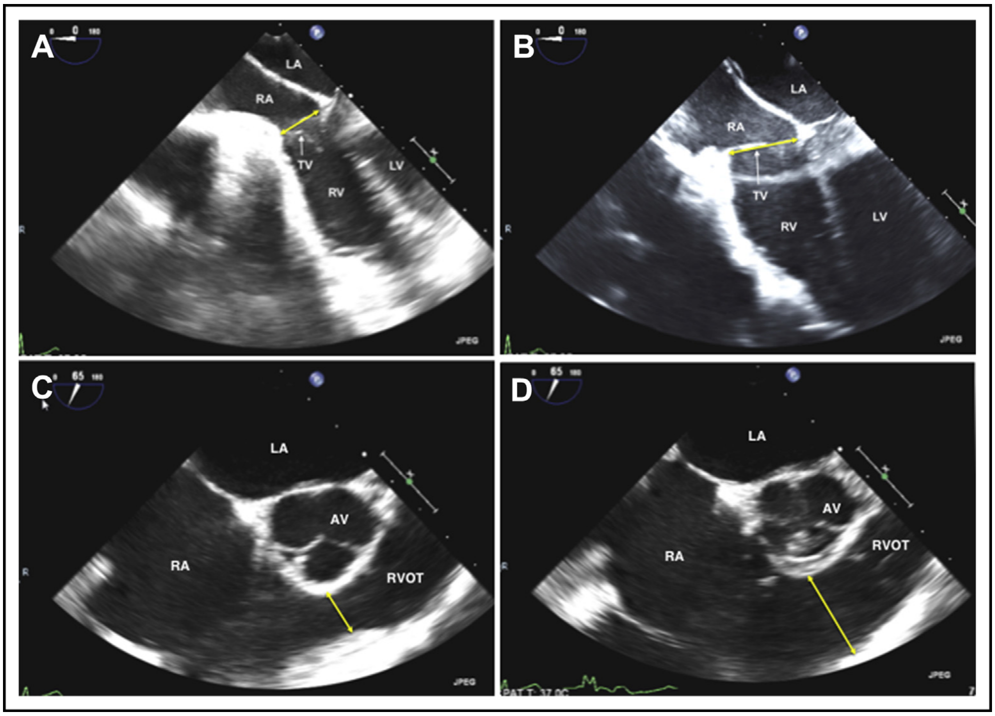

Figure 3 Transesophageal echocardiographic images showing the effect of pectus repair surgery on right heart chamber size. Tricuspid annulus diameter is shown by a yellow arrow in A and B and RVOT diameter by a yellow arrow in C and D. (A) It shows the midesophageal, 4 chamber view demonstrating the compression of RA, tricuspid annulus, and basal portion of RV before surgical repair. Prolapsing appearing TV is shown by a white arrow in A. There was a 1.6 cm increase in tricuspid annulus diameter (B). In the same view it demonstrates the relief of the compression of RA, tricuspid annulus, and basal RV immediately after surgery. Note the normal appearance of TV in B (white arrow). (C and D) These are the ME, aortic valve short-axis views demonstrating RVOT (yellow arrow, presurgery) and the same region (yellow arrow) (D) after surgery. There was a 1.13-cm increase in the RVOT diameter. AV = aortic valve; LA = left atrium; TV = tricuspid valve. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

patients and demonstrated a correlation between the severity of deformity as measured by CT- and/or MRI-derived Haller index and cardiopulmonary function as measured by LV ejection fraction, FEV1, and ratio of FEV1 to forced vital capacity (FEV1/FVC). Although we did not find a correlation between Haller Index and RV function, such as RV stroke volume and RV cardiac output, we found correlations between both preoperative RA and tricuspid annulus size and preoperative RV stroke volume. This finding indicates that preoperative RA and tricuspid annulus size, measured by TEE, correlate better with preoperative RV function than the Haller index.

In our patient cohort, we demonstrated immediate postoperative structural and functional improvement of the right heart by intraoperative to TEE after modified Nuss surgical PE repair.

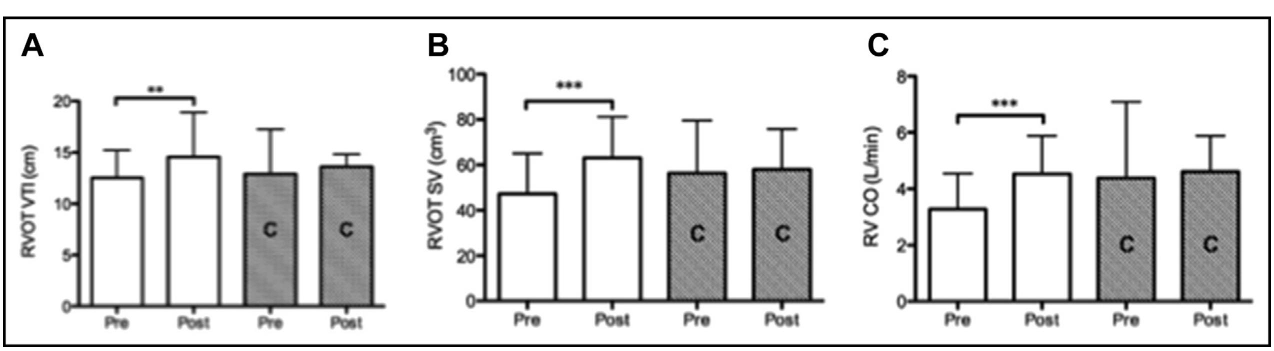

Figure 4 Changes in right heart function in 41 patients who underwent Nuss surgical PE repair and in whom echo Doppler measurements were performed prerepair and postrepair and in the 17 controls (labeled C) who underwent bar removal. Improved RV function is shown postsurgical PE repair vs baseline (***P* < .01, ****P* < .0001 in paired, Student *t* test) but not in the control group. (A) RVOT VTI, (B) RVOT SV, (C) RVOT CO. Data are mean ± SD. CO = cardiac output; RVOT = right ventricular outflow tract; SD = standard deviation; SV = stroke volume; VTI = velocity time integral.

Structural Changes, Exercise Capacity, and Pulmonary Function Studies After Pectus Excavatum Repair

Relief of cardiopulmonary compression by PE surgery should result in an improvement in exercise capacity as well as in pulmonary function. Although some reported the positive effect of pectus repair surgery,[2–8] other studies[9–14] showed nonsignificant results. Increased exercise performance postoperative may result from multiple factors including relief of cardiac chamber compression, an increase in the anterior-posterior thoracic dimension which facilitates filling of the heart,[3] improved self-rated satisfaction of bodily appearance,[4] and motivation to exercise resulting in an improvement in functional capacity.[3] Postoperative improvement in both cardiac function and exercise capacity has been shown in some recent studies,[2,3,7,16,17] for ventricular dimensions,[2,3] stroke volume,[7,10,16,17] RV ejection fraction,[7] or cardiac output.[10,16,17] The three studies conducted by the group of Sigalet et al[10,16,17] indicated that early improvements in cardiac function were sustained during longer term follow-up. Studies reporting negative effects after surgical repair did not perform echo assessment nor directly compare changes in cardiac function with change in exercise capacity.[9–13,28] Hence data from the published studies should be considered as indirect supportive evidence, and direct comparisons should be performed in future studies. To the best of our knowledge, ours is the largest study using intraoperative TEE to study the effect of Nuss repair surgery in adult PE patients.

Conclusions

In patients with PE deformity, surgical correction and relief of compression significantly improved right heart chamber size along with improvement in right heart function. TEE was a valuable tool for intraoperative assessment of changes in right heart structure. Further studies need to evaluate if improvements seen in echo parameters after PE surgery translate into longer term improvement in exercise capacity.

Limitations

This study is a retrospective study, and the measurements relied on the quality of TEE images. Patients with incomplete data or technically difficult images were excluded. Cardiac function was only evaluated in a subset of patients; however, the number was still comparable to all other previous studies. Respiratory cycle may influence cardiac chamber dimension; however, care was taken to make measurements in held respiration in patients with significant respiratory changes in cardiac dimensions. The reader was not blinded to prerepair vs postrepair images; however, interobserver variability data suggest that the effects we observed on chamber size and stroke volume are real effects related to relief of pectus deformity. Changes in hemodynamic conditions before surgery and after surgery may influence chamber dimensions as well as cardiac output; however, we did not observe any changes in heart rate or blood pressure among patients. In addition, no volume infusion, blood transfusion, or inotropic support was needed in patients indicating that the postoperative functional improvement was from the relief of right heart compression rather than from a change in hemodynamic state.

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Discussion

Discussant

Dr. David J. Cole (Charleston, SC): I would like to thank the Southwestern Surgical Congress for the opportunity to discuss this article and also to thank the authors for allowing me to review the article in a timely manner.

The authors' retrospective evaluation was performed of 168 adult patients who underwent a modified Nuss pectus excavatum (PE) repair with intraoperative transesophageal echocardiography (TEE) from 2011 to 2014. Seventeen patients with prior PE repair undergoing bar removal acted as controls.

Until the mid 1990s, the operative treatment of PE had been fairly well standardized and was based on the open operation originally described by Ravitch in 1949. Few variations to his original description have been added, and the operation became almost universal acceptance by pediatric and thoracic surgeons as the standard for treatment of this condition. Several published series demonstrated excellent results with low-complication rates despite the fairly radical nature of the Ravitch operation. The procedure is performed via an anterior chest wall exposure, creation of muscle and skin flaps, extensive resection of the affected cartilages, and sternal osteotomy. Frequently, a transverse stainless steel plate or an artificial mesh is placed to support the sternum during the healing phase, minimizing the risk of pectus recurrence.

In 1987, during the early stages of laparoscopic and minimally invasive surgery, Donald Nuss reported the 1st minimally invasive operation for the correction of pectus excavatum. Not until May of 1997 was this new and innovative technique introduced to the American Pediatric Surgical Association and, subsequently, published in the *Journal of Pediatric Surgery.* Because of the excellent results obtained with this new technique and because of the less radical nature of the operation, the popularity of this technique has grown dramatically.

Although it is clear that PE may cause physiologic symptoms and impairment by compression of the right heart chambers and limitation of diastolic filling, and the Nuss procedure provides a potentially minimally invasive approach to the repair of this congenital abnormality, the actual cardiopulmony implications and benefits of surgical correction on PE deformity have been more implied than firmly established, especially in an adult population where the overall reported experience is smaller.

In this presentation, the authors reported an increase in right atrial size, tricuspid annulus, right ventricular outflow tract, and cardiac output after correction of the pectus. As noted, the implication that pectus correction results in cardiopulmonary improvement has been demonstrated by a few other studies but has remained controversial. A large multicenter study on pediatric patients published in the *Journal of the American College of Surgeons* in 2013 by Dr. Nuss and his collaborators demonstrated improvement in static pulmonary function and, most importantly, improvement in oxygen consumption as measured during incremental exercise. Such findings corroborate with the observations reported here, and I would like to commend the authors for adding their retrospective series that contains some comparable TEE data. I have several questions for the authors:

1. Given that often a driving force behind repair of pectus excavatum is cosmetic or psychological in nature, did you perform any preoperative and postoperative psychological parameter assessment in your patient populations?
2. The choice of 17 patients who had previously undergone PE repair is informative, however, would not appear to be a true control group. Did you have any evaluation of age or case-control–matched adults who did not have PE?
3. It was implied, but unclear to this discussant, that the postoperative functional evaluation was in the perioperative period. Given the potential for more longitudinal improvement in cardiac function, did the authors have any follow-up of patients over time, that is, after removal of the bar and subsequently?
4. Was there any correlation discernable between the measured Haller index sand cardiopulmonary functional improvement noted by the authors?

5. Given the age of this population, average 33 years, it would be informative to understand the selection criteria used by the authors possibly besides the measurement of the Haller index that were used for recommending surgery.

Finally, was there any postoperative complications of note? This was not mentioned in the article. It is known that adult patients with pectus excavatum who undergo Nuss procedure are at higher risk for complications, particularly life-threatening complications, in the adult population. Any comments would be appreciated.

Dr. Chieh-Ju Chao: We agree that there is a cosmetic effect and also the subsequent repair may improve the patient's self-confidence. This may also improve their exercise performance after surgical repair. We did not assess the in our present study, we are trying to study the cosmetic and also self-confidence rating in 2nd question about the control group of the 17 patients that received bar removal later we selected this cohort since we did not find age matched non pectus patient cohort who had undergone an intra-operative TEE during any kind of surgery.

Regarding your 3rd question, this was an acute intra-operative TEE study during pectus surgery without longitudinal assessment after bar removal. However currently we are performing a longer term evaluation on our patients who were available for follow up.

Also, this is also related to the 4th question regarding the age of our patient selection. Basically, we are focused on the adult patients. The youngest patient is 18 years old the oldest patient is 71 years old. As stated in the our report we used significant and/or progressive "unexplained" cardiopulmonary symptoms and psychological issues in our indications for surgery besides CT and MRI derived compression indices.

We did not postoperative complications in our study.

Dr. Danny Chu (Pittsburgh, PA): You mentioned in your concluding slide that TEE is a useful adjunct. Do you think TEE should become the standard of care for these procedures? If so, why?

Dr. Chieh-Ju Chao: For pectus patients, the inward deformity of the chest may create a narrow window for transthoracic echocardiography assessment. Unlike other reports that found TEE imaging difficult we found that in expert hands TEE is feasible in nearly all patients and does provide important information regarding changes in cardiac geometry following surgery. At our center TEE is routinely performed before and after Nuss surgery and should be considered by others as routine during pectus surgery.