Two-dimensional and three-dimensional echocardiographic assessment of right ventricular function in patients with pectus excavatum, before and after surgery

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Pectus excavatum (PE) is one of the most common congenital chest wall deformities observed in clinical practice and has an estimated prevalence in the range of one in 500 to one in 1000 among children; it is characterized by posterior displacement of the inferior sternum and the cartilaginous-rib attachments.[1] The physiological symptoms and impairment which arise due to PE vary, as the depression of the anterior chest wall compresses the right heart chambers, causing various morphological and functional cardiac alterations. Some patients with PE experience progressive worsening of cardiopulmonary function with increasing age.[2] Therefore, surgical repair aimed at correcting the disorder is strongly recommended.[1,3] Several studies demonstrated an improvement in pulmonary function and exercise capacity in patients with PE after surgical repair.[3-5] However, since the shape of the right ventricle (RV) is irregular and the function is difficult to assess using two-dimensional (2D) transthoracic echocardiography (TTE), the availability of cardiac benefits, especially RV function improvement, of surgical repair for PE deformity remains controversial according to previous studies that assessed RV function using 2D TTE.[4,5] In contrast, three-dimensional (3D) TTE demonstrates better visualization and localization of the RV and can evaluate RV function more accurately.[6,7] Therefore, we used 3D TTE to evaluate RV function before and after surgery in a group of patients who underwent surgical repair, to confirm the effects of PE deformity and improvements in RV structure and function after surgical correction.

A retrospective cohort of 21 patients who were diagnosed with PE as an isolated chest deformity and who underwent surgical correction at the Beijing Children's Hospital, Xicheng District, Beijing between July 2016 and February 2017 were included in this study. Exclusion criteria were other congenital heart diseases or Marfan syndrome. To demonstrate the structure and evaluate the function of the RV, all patients underwent 2D and 3D TTE pre-operatively, on the third post-operative day, and at the 3-year follow-up before the bar removal procedure was performed. A group of 21 age- and sex-matched healthy children without chest wall abnormalities underwent TTE as the control group. The examinations were analyzed offline by independent observers who were blinded to the clinical characteristics of the participants. The study was approved by the Institutional Ethics Committee (code: 2020-Z-026); a patient consent form was signed by each patient's parent.

All patients underwent comprehensive echocardiography using a Philips X5-1 MHz transducer coupled with a Philips iE33 ultrasound system (Philips Healthcare, Andover, MA, USA). An apical four-chamber view can usually visualize the extrinsic compression to the RV. Modifying standard views should be used due to the limitations of the abnormal anatomy before surgery or of the metal bar after surgery. In addition to the standard echocardiographic evaluation, the RV transverse, anteroposterior, and longitudinal end-diastolic diameters, the tricuspid valve annulus (TVA) diameter, the tricuspid annular plane systolic excursion (TAPSE), the RV fractional area change (FAC), and the pulsed tissue Doppler systolic (S') wave at the TVA were measured. An RV-focused apical four-chamber view was used to acquire the 3D dataset. Full volume loops were acquired over four cardiac cycles, and

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analysis of RV function was performed offline. The offline software TOMTEC-ARENA, TTA 2.30 algorithm (TomTec Imaging Systems, Munich, Germany) tracked the endocardium of the RV, measured the RV longitudinal strain (LS) of the septum and free wall by speckle-tracking analysis, and measured the RV end-diastolic volume (EDV), the RV end-systolic volume (ESV), the RV stroke volume (SV), and the RV ejection fraction (EF) using 3D voxel pixel analysis. The average values of three measurements of all these parameters from different cardiac cycles were calculated for the final data analysis. All measurements were performed by a single experienced observer. Nine results of three patients were randomly selected for repeated measurements of each 3D parameter. Observer 2, blinded to the values measured by Observer 1, measured the stored images to assess interobserver variability.

All data, expressed as mean ± standard deviation, were analyzed using SPSS software, version 25.0 (IBM SPSS Statistics for Windows, Armonk, NY, USA). Using the paired two-tailed Student's t test, echocardiographic data were compared between the pre-operative and control groups, pre-operative and post-operative groups, post-operative and control groups, and 3-year follow-up and post-operative groups. To assess reproducibility, the measurements of the two observers were analyzed using the paired two-tailed Student's t test. Bland-Altman plots were applied to determine interobserver variabilities. For all comparisons, P values < 0.05 were regarded as statistically significant.

A total of 21 patients with PE who underwent surgical repair were enrolled in our study. The mean patient age was 10.74 ± 3.50 years (range: 4.1–15.2 years); 13 patients (61.9%) were male. Baseline characteristics of the surgery and control groups were not significantly different. The mean values of the echocardiographic measurements, including those at the pre-operative, post-operative, and 3-year follow-up stages, and those of the control group, are summarized in Table 1.

Compared with the control group, RV EDV, RV SV, RV EF, RV FAC, RV free-wall LS, RV transverse diameter, and anteroposterior and longitudinal end-diastolic diameters were significantly decreased in the patients with PE. There were no significant differences between the patients with PE and the control group for RV ESV, RV septum LS, TAPSE, TVA, and S'. Compared with pre-surgery measurements, RV EDV, RV SV, RV EF, RV FAC, and RV transverse and anteroposterior diameters were significantly increased, whereas RV ESV was significantly decreased, after surgical correction. No significant changes were observed pre- and post-surgery in the RV free-wall LS, the RV septum LS, TAPSE, TVA, the RV longitudinal end-diastolic diameter, and S'. There were no significant differences in any of the RV parameters between the PE patients post-surgery and the control group. Compared with post-surgery measurements, the RV anteroposterior and longitudinal end-diastolic diameters were significantly increased at the 3-year follow-up [Supplementary Figure 1, http://links.lww.com/CM9/A477]; however, the other RV parameters were not significantly different. The mean RV EF measurements ($n = 9$) of the two observers were 51.97 ± 6.19 and 52.92 ± 7.68 ($P = 0.466$). There was a linear correlation ($r = 0.88$, $P = 0.002$) between the two observers.

PE accounts for more than 90% of all congenital chest wall abnormalities in which posterior displacement of the sternum reduces the anteroposterior dimension of the chest and causes compression and displacement of the heart.[1] By deployment of stress echocardiography, previous studies focused on the impaired cardiopulmonary function and exercise intolerance that is attributable to cardiac compression caused by PE.[1,3] As the RV is located directly behind the sternal plate and has a thin wall and low pressure, it is most likely to be compressed by the PE deformity. Therefore, it is important to accurately assess RV morphology and function in patients with PE. Because of the unique geometry of the RV, the degree of RV compression and impairment of RV function is often

Table 1: Echocardiographic parameters of pre-surgery, post-surgery, 3-year follow-up of patients with pectus excavatum and control group.

Parameters	Control group	Pre-surgery	Post-surgery	3-year follow-up
RV_d – transverse (mm)	26.76 ± 4.57	$20.65 \pm 4.76^*$	$25.66 \pm 5.13^\dagger$	26.05 ± 3.64
RV_d – anteroposterior (mm)	12.25 ± 1.67	$9.02 \pm 1.26^*$	$11.55 \pm 1.64^\dagger$	$13.09 \pm 1.67^\ddagger$
RV_d – longitudinal (mm)	52.74 ± 10.11	$47.14 \pm 8.55^*$	48.45 ± 6.78	$53.29 \pm 1.67^\ddagger$
TVA (mm)	24.15 ± 3.36	21.18 ± 6.22	24.80 ± 4.90	24.80 ± 2.91
TAPSE (mm)	21.25 ± 3.47	21.22 ± 3.27	24.21 ± 6.07	21.87 ± 4.21
RV FAC (%)	43.45 ± 7.51	$31.15 \pm 9.63^*$	$43.85 \pm 9.96^\dagger$	42.05 ± 3.68
S' (cm/s)	12.25 ± 2.26	12.79 ± 3.11	13.54 ± 3.61	11.39 ± 2.32
RV septum LS (%)	-15.45 ± 6.11	-16.21 ± 6.04	-14.49 ± 8.10	-17.22 ± 6.59
RV FW LS (%)	-27.22 ± 5.17	$-23.32 \pm 4.39^*$	-25.74 ± 7.51	-28.56 ± 4.41
RV EDV (mL)	59.45 ± 12.53	$47.85 \pm 13.15^*$	$57.43 \pm 13.75^\dagger$	57.15 ± 9.69
RV ESV (mL)	25.26 ± 6.65	26.52 ± 6.69	$24.26 \pm 6.99^\dagger$	24.19 ± 4.10
RV SV (mL)	34.31 ± 7.14	$21.38 \pm 6.89^*$	$33.18 \pm 7.63^\dagger$	32.95 ± 5.85
RV EF (%)	58.81 ± 5.83	$44.32 \pm 3.60^*$	$57.98 \pm 4.52^\dagger$	58.81 ± 5.83

Data are presented as mean ± standard deviation. $^*P < 0.05$, compared with control group. $^\dagger P < 0.05$, compared with pre-surgery. $^\ddagger P < 0.05$, compared with post-surgery; d: Diameter; EDV: End-diastolic volume; EF: Ejection fraction; ESV: End-systolic volume; FAC: Fractional area change; FW: Free-wall; LS: Longitudinal strain; RV: Right ventricle; S': Doppler systolic; SV: Systolic volume; TAPSE: Tricuspid annular plane systolic excursion; TVA: Tricuspid valve annulus.

difficult to assess using 2D TTE.[6,8] This difficulty explains why the physiological implications of PE on heart function have been debated over the years.

We used 3D and traditional TTE to assess RV abnormalities in patients with PE. We compared the echocardiographic parameters between the patients with PE and the control group, and demonstrated that RV function, volume, and dimensions were decreased in the patients with PE. The results of 3D TTE confirmed that the deformity caused by PE impaired the RV EF and cardiac output, and limited expansion during diastole. 2D TTE showed that patients with PE have smaller RV dimensions and FAC, and the 2D speckle-tracking image showed the abnormality of the RV free-wall LS. These findings suggest that PE deformity has a harmful effect on RV morphology and function.

Many studies have confirmed that exercise capacity and pulmonary function can be improved after the relief of PE cardiopulmonary compression through surgical repair.[1,3] However, these cardiac benefits are still controversial. Using 2D TTE and 2D transesophageal echocardiography (TEE), recent studies have found improvements in RV function after surgery.[3-5] However, few studies have evaluated the effect of PE correction on RV function using 3D TTE. In our study, we observed that the surgical correction of sternal depression led to the improvement of RV compression and function. Comparing the pre-operative and post-operative echocardiographic parameters, we found that RV function, volume, and dimensions were significantly increased after surgery. 3D TTE confirmed that surgery had beneficial effects on RV function. Moreover, the post-operative and control group data were not significantly different, indicating that the cardiac impairment caused by PE deformity is reversible, and that normal function can be recovered through surgical repair in pediatric patients.

Comparing the post-operative and 3-year follow-up data, the RV anteroposterior and longitudinal dimensions increased; however, no 3D parameter was significantly different. These results indicate that early improvements in RV function after surgical correction were sustained for at least 3 years, and that the RV anteroposterior and longitudinal dimensions increased within the bounds of the patients' thoracic growth. However, the RV EDV, the RV SV, and the RV transverse dimension did not increase as the children grew; the main reason for this may be the restriction imposed by the retrosternal bar.

In conclusion, PE deformity causes impairment of RV morphology and function, which can be relieved through corrective surgery in pediatric patients. Following corrective surgery, a sustained improvement in RV function was observed, and the dimensions of the RV increased during the growth of the patients.

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Conflicts of interest

None.

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