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Impact of surgical correction of pectus excavatum on cardiac function: insights on the right ventricle. A cardiovascular magnetic resonance study†

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Abstract

OBJECTIVES: Pectus excavatum (PE) is often regarded as a cosmetic disease, while its effect on cardiac function is under debate. Data regarding cardiac function before and after surgical correction of PE are limited. We aimed to assess the impact of surgical correction of PE on cardiac function by cardiovascular magnetic resonance (CMR).

METHODS: CMR at 1.5 T was performed in 38 patients (mean age 21 ± 8.3; 31 men) before and after surgical correction to evaluate thoracic morphology, indices and its relation to three-dimensional left and right ventricular cardiac function.

RESULTS: Surgery was successful in all patients as shown by the Haller Index ratio of maximum transverse diameter of the chest wall and minimum sternovertebral distance [pre: 9.64 (95% CI 8.18–11.11) vs post: 3.0 (2.84–3.16), $P < 0.0001$]. Right ventricular ejection fraction (RVEF) was reduced before surgery and improved significantly at the 1-year follow-up [pre: 45.7% (43.9–47.4%) vs 48.3% (46.9–49.5%), $P = 0.0004$]. Left ventricular ejection fraction was normal before surgery, but showed a further improvement after 1 year [pre: 61.0% (59.3–62.7%) vs 62.7% (61.3–64.2%), $P = 0.0165$]. Cardiac compression and the asymmetry index changed directly after surgery and were stable at the 1-year follow-up [3.93 (3.53–4.33) vs 2.08 (1.98–2.19) and 2.36 (2.12–2.59) vs 1.38 (1.33–1.44), respectively; $P < 0.0001$ for both]. None of the obtained thoracic indices were predictors of the improvement of cardiac function. A reduced preoperative RVEF was predictive of RVEF improvement.

CONCLUSIONS: PE is associated with reduced RVEF, which improves after surgical correction. CMR has the capability of offering additional information prior to surgical correction.

Keywords: Right ventricle • Pectus excavatum • Minimally invasive repair of pectus excavatum • Cardiovascular magnetic resonance • Thoracic index

INTRODUCTION

Pectus excavatum (PE) accounts for ∼90% of all chest wall deformities. It has an estimated occurrence of 1 in 400 to 1 in 1000 live births with males affected 3–5 times more often than females [1]. The characteristic feature of PE is a reduction of the sternovertebral distance, which is associated with the leftward displacement and rotation of the heart. As a consequence, the right ventricle is often impressed, dislocated and rotated (Fig. 1). Mitral valve prolapse and other functional abnormalities may occur [2]. Patients with PE suffer from unspecific symptoms and subjectively decreased exercise capacity. However, objective data on impaired cardiac or pulmonary function are not easy to confirm. Due to specific anatomy, echocardiography may be insufficient to objectify patient's complaints and follow postoperative changes as reflected and discussed in the literature [3, 4]. In the current literature, most of the echocardiographic data focus on the left ventricle, whereas data on the anatomically

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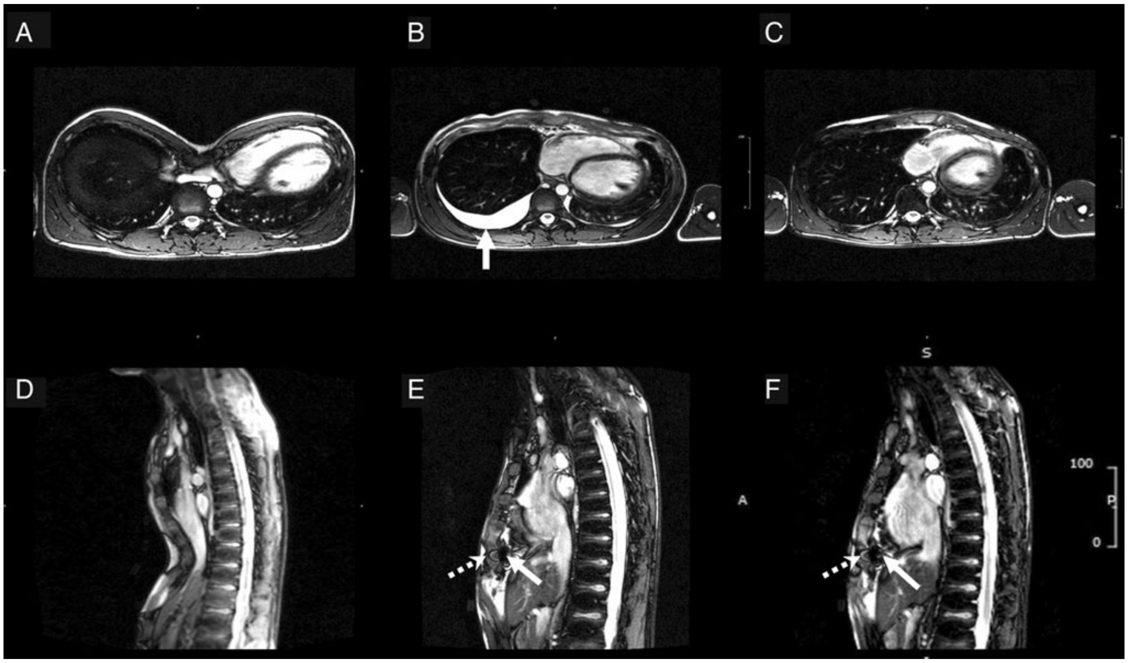


Figure 1: Changes in thoracic and cardiac morphology during follow-up—case example. CMR overview images in different orientations: axial (upper row, **A**–**C**) and sagittal (bottom row, **D**–**F**). The retrosternal implanted stainless bar (white arrows in E and F). Artefact due to the implanted titanium bar (dotted white arrows in E and F). (A and D) Preoperative views demonstrating the amount of thoracic deformity and cardiac compression. (B and E) Follow-up 1 after surgical correction (Day 12) demonstrating normalization of thoracic shape and cardiac decompression, pleural effusion (white arrow in B). (C and F) Follow-up 3 after 20 months, showing a stable result and complete resolution of pleural effusion. CMR: cardiovascular magnetic resonance.

more affected right ventricle (RV) are limited [5]. This phenomenon is well known in cardiology and is attributable to the challenging quantification, as the RV does not follow a geometrical assumption. On the other hand, the RV has prognostic impact on different entities [6]. In congenital heart disease, most of the prognostic data are based on cardiovascular magnetic resonance (CMR) as a standard of three-dimensional (3D) quantification of cardiac function [7]. CMR does not depend on thoracic anatomy and allows a significant sample size reduction in comparison with echocardiography for the assessment of cardiac morphology, and is so far accepted as the gold standard [8]. Currently, the clinical decision-making on surgical correction in PE includes different factors like shape of thoracic deformation, changes of cardiac morphology and clinical and psychological aspects [9]. The cardiac function itself does not play an established role due to the limited knowledge on modification of cardiac morphology by thoracic surgery [9, 10]. We assume that additional 3D information on cardiac impairment may help guide therapeutical decision-making. Based on this consideration, we applied CMR to assess cardiac morphology and its relation to thoracic anatomy in patients with PE before and after surgical correction including a 1-year follow-up.

MATERIALS AND METHODS

Patients

The Department for Paediatric Surgery of our hospital is a high-volume centre for correction of thoracic abnormalities. They refer candidates for corrective surgery to CMR for assessment of cardiac function and exclusion of coexistent anomalies. We used a dedicated scan protocol developed only for this patient cohort. We have evaluated the consecutive scanned patients from August 2009 to November 2011. We excluded subjects with other comorbidities or contraindications for CMR. Patients who underwent pre- and postoperative CMR examinations were evaluated. The mean time to follow-up was 13 ± 7 days (FU1), 120 ± 47 days (FU2) and 472 ± 162 days (FU3) after surgical correction.

Thoracic surgery

Thoracic surgery using minimally invasive repair of PE, a modified Nuss procedure, was performed based on the usual clinical indication [9, 11]. Details of the operative technique are given by Schaarschmidt *et al.* [12]. The modified Nuss procedure is characterized by the following modifications: the surgeons use a bilateral thoracoscopy, helpful for retrosternal dissection in extremely deep thoracical deformations. Furthermore, the thoracic muscles are dissected off the ribs by diathermy to provide ample muscle pockets. The bars ends and stabilizers are placed into the submuscular pockets directly on the ribs. The bars are fixed to adjacent ribs by pericostal sutures under thoracoscopic assistance. Stabilizers are jammed on the bent bar by a bone hammer and fixed without wires. Bars and stabilizers receive pericostal figure of eight fixations through their end holes. If a second bar was required, it was inserted through the same incisions, then the first and second bars were fixed by 14–18 and 6–10 absorbable pericostal sutures, respectively.

Cardiovascular magnetic resonance

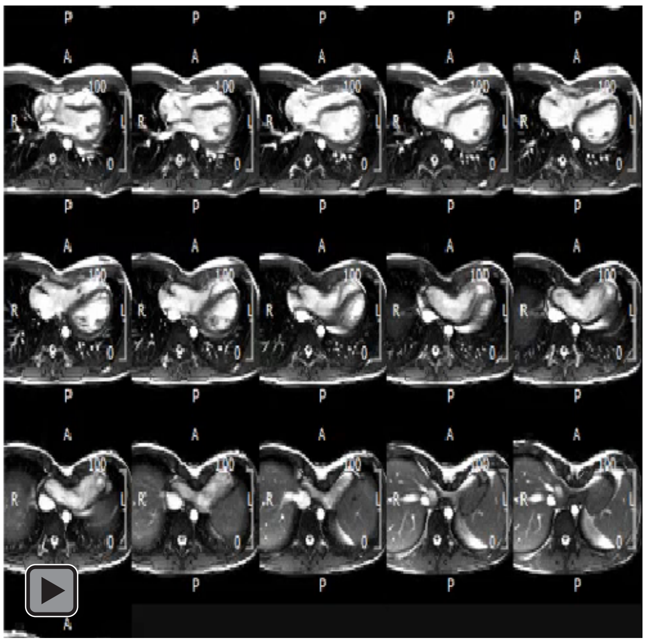
All CMR studies were performed on a 1.5-T scanner (Magnetom Avanto, Siemens Healthcare, Erlangen, Germany) using a 12-channel phase array coil. We aimed to evaluate the cardiac function and its relationship to the thoracic anatomy using the following protocol.

Chest anatomy was assessed using a standard, non-breath-hold half-Fourier single-shot turbo spin echo sequence (HASTE) and a true fast imaging with steady-state free precession sequence (SSFP) both in sagittal and in axial orientation.

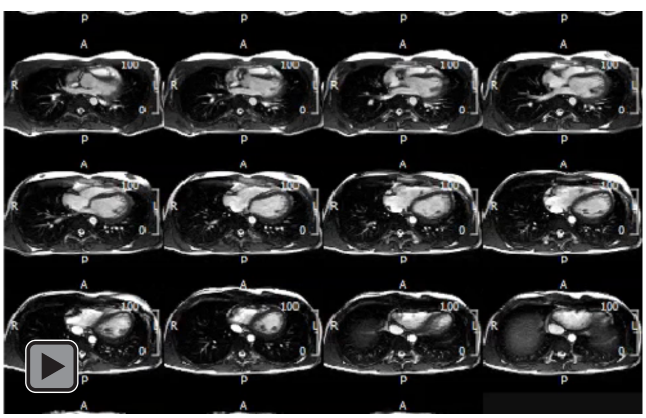
Cardiac function (CMR protocol) was assessed applying state-of-the-art SSFPs. Full coverage of the RV was based on a stack of axial of slices [cine-SSFP, slice thickness (slth) 6 mm, no gap, repetition time (TR)/echo time (TE) 33.6/1.18 ms, flip angle (FA) 70°]. Representative examples of pre- and postoperative evaluation in one typical case are given in Videos 1 and 2. For left ventricular (LV) assessment of the long axis (LAX) as well as short axis (SAX), cine images (cine-SSFP, TR/TE 34.68/1.22 ms and FA 80°) were acquired. LAX was performed as four-, two- and three-chamber views (slth 6 mm). Full coverage of the LV was based on a stack of SAX (slth 7 mm, no gap).

Image evaluation

All images were analysed using CMR42 (circle cvi, Canada version 4.1.8). Chest anatomy was quantified using five different



Video 1: Preoperative evaluation in a typical case. A stack of axial slices applying cine images from the base to the apex covering the whole right ventricle. Right ventricular distortion and compression between the sternum and vertebral column could be clearly seen.



Video 2: The same patient as demonstrated in Video 1. Postoperative evaluation. Changes in right ventricular shape and heart position in the thorax observed by cardiovascular magnetic resonance, illustrated by applying cine images in axial orientation.

parameters as described in the literature and illustrated in Fig. 2. The Haller Index was calculated using the minimum sternovertebral distance (D) and the maximum transverse diameter of the chest wall (T) [13]. The chest wall asymmetry index was calculated as L/R ratio from assessed antero-posterior diameter of the left hemithorax (L) and antero-posterior diameter of the right hemithorax (R). The indices were measured on the axial images using the corresponding sagittal plane as the second localizer. The relation between thoracic deformity and its impact on the heart itself is described by the cardiac deformity indexes (CDIs). These are the cardiac compression index (CCI), the cardiac asymmetry index (CAI) and the cardiac left lateral shift (CLLSH). They were evaluated according to methods previously described [14, 15]. In short, all CDIs were obtained in axial-oriented images. The CCI is based on the H/M ratio, where H indicates the widest transverse diameter of the heart and M the narrowest antero-posterior diameter of the heart at the xiphoid process. The CAI is based on the P/M ratio, where P indicates the widest paramedian diameter of the heart and M as explained above. CLLSH is a measure of cardiac displacement into the left hemithorax due to chest wall abnormality. For this index, the maximum lateral distances of the left and right cardiac borders are measured from the midline (sterno-spinal line). CLLSH (%) was calculated using the formula described by Saleh *et al.* [15].

Cardiac morphology was quantified following the recently published society of cardiovascular magnetic resonance post-processing guidelines [16]. The RV was assessed in the axial orientation (Fig. 3). We quantified end-diastolic (RVEDV) and end-systolic volumes. RV trabeculae were defined as part of the blood pool while tracing the endocardial border. The right ventricular ejection fraction (RVEF) and right ventricular stroke volume (RVSV) as well as indexed (BSA) values were calculated. The LV endocardium and epicardium were traced manually from end-diastolic and end-systolic phases defined in the SAX. Papillary muscles were excluded from the LV volume. Measurements were normalized to body surface area and used for comparative intra-individual analysis. Interobserver variability analysis was performed for RV volumes in 10 randomly chosen datasets.

Statistical analysis

Statistical analyses were performed with SAS 9.2 (SAS Institute, Cary, NC, USA). Continuous variables are displayed as least square means (LS mean) with 95% confidence intervals based on a linear mixed model with the baseline value as a co-factor. This model was also used to assess statistical significance. Baseline characteristics as well as thoracic indices, ejection fraction, end-diastolic volume, end-systolic volume, stroke volume of the right and left ventricle were assessed in a logistic regression model for their predictiveness of the improvement of cardiac function postoperatively by at least 3.69%. This cut-off for improvement was based on the standard deviation as assessed by a Bland–Altman analysis between two readers for 10 randomly chosen patients. Receiver operating characteristic (ROC) curves were produced for the significant factors. An optimal cut-off was assessed using the Youden index, i.e. the value, where the sum of the sensitivity and the specificity reaches its maximum. Correlations between cardiac function and anatomical indices were assessed by Spearman's rank correlation coefficient. Two-sided $P \leq 0.05$ were regarded as statistically significant.

The ethical review committee of our institution gave ethical approval for retrospective analysis of consecutively collected data (EA1/079/13).

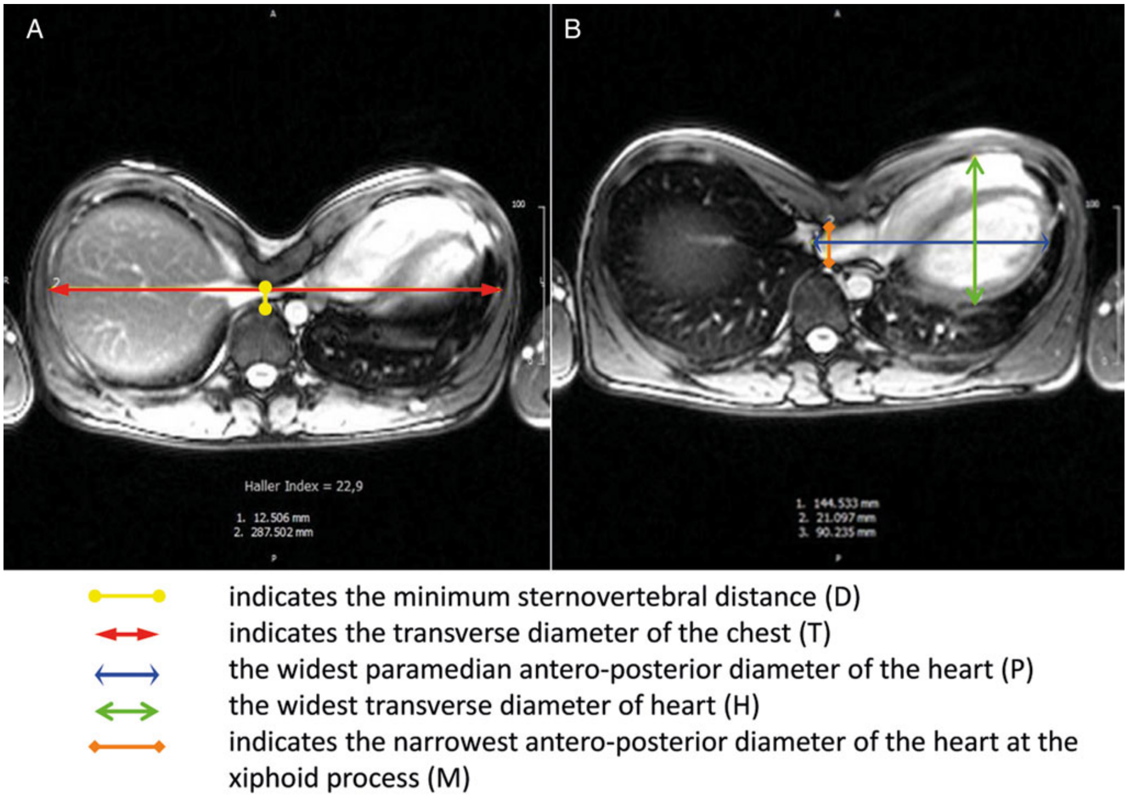


Figure 2: Quantification of thoracic and cardiac indices. (**A**) The Haller Index calculated from the minimum sternovertebral distance and transverse diameter of the chest (T/D ratio). (**B**) Cardiac compression index (CCI) based on the H/M ratio; cardiac asymmetry index (CAI) based on the P/M ratio.

RESULTS

Patients

A total of 96 consecutive patients referred to CMR for preoperative scans met the study criteria. Forty-nine subjects had only baseline scans, and there was no further follow-up mainly due to the international character of the patient population. The remaining 47 patients were rescheduled, but 9 had to be excluded due to various reasons. Two patients discontinued the scan due to transient heating and not otherwise specified thoracic sensations, and in 1 case a gating error occurred.

Six of the 47 patients had to be excluded from the analysis due to artefacts related to the stainless bar. A blinded reader prior to analysis made the decision if the discrimination of the endocardial borders was hampered. Finally, 38 consecutive patients with PE (31 male, age 12–43 years) completed the baseline and last follow-up scans, and 27 patients completed all four scans. The number of patients included in the analysis at the time of follow-up was 27 for FU1 (13 ± 7 days), 33 for FU2 (120 ± 47 days) and 38 for baseline and FU3 conducted 472 ± 162 days after surgical correction.

Chest anatomy

All chest wall indexes showed a significant change in all patients, indicating a successful surgery (*P*-value for all <0.0001 pre versus post). That was already detectable at FU1 and remained stable during the whole follow-up period. Postoperative effusions were a common finding in our patients: FU1 (at 13 ± 7 days) could be conducted in 27 of the 38 patients included in the study; 24 of the 27 patients had postoperative pleural effusions and 3 of 27 had also pericardial effusions early after surgery (see also Fig. 1). All of these resolved during follow-up (FU3). CCI and CAI were significantly modified as well ($P < 0.001$ for both pre- and post-surgery) as shown at FU1. The results remained stable until the last follow-up (Table 1). The reduction in the CLLSH occurred not directly postoperatively but at FU2 and remained significantly reduced afterwards compared with baseline (pre: 83.4% vs FU3: 78.1%, $P = 0.0075$).

Cardiac function

The assessment of cardiac morphology gave new insights on both cardiac ventricles. Details are given in Table 2. In summary, the RVEF was reduced before surgery and increased significantly after surgery, remaining improved at FU3 ($P = 0.0004$ for pre versus FU3). Changes in the RVEF (baseline versus FU3) for each subject and the mean value of the entire group are illustrated in Fig. 4. Whereas the RVEDV remained unchanged at all time points, the RVSV increased significantly ($P = 0.0167$). LV ejection fraction (LVEF) was within the normal range preoperatively, and showed a slight increase at FU3 (pre versus FU3, $P = 0.0165$).

Relations between cardiac function and thoracic and cardiac deformity indices

There were no correlations between the chest anatomy indices, and cardiac function when normalized to body surface area. The thoracic indices were also not predictive for changes in RV or LV function in our population.

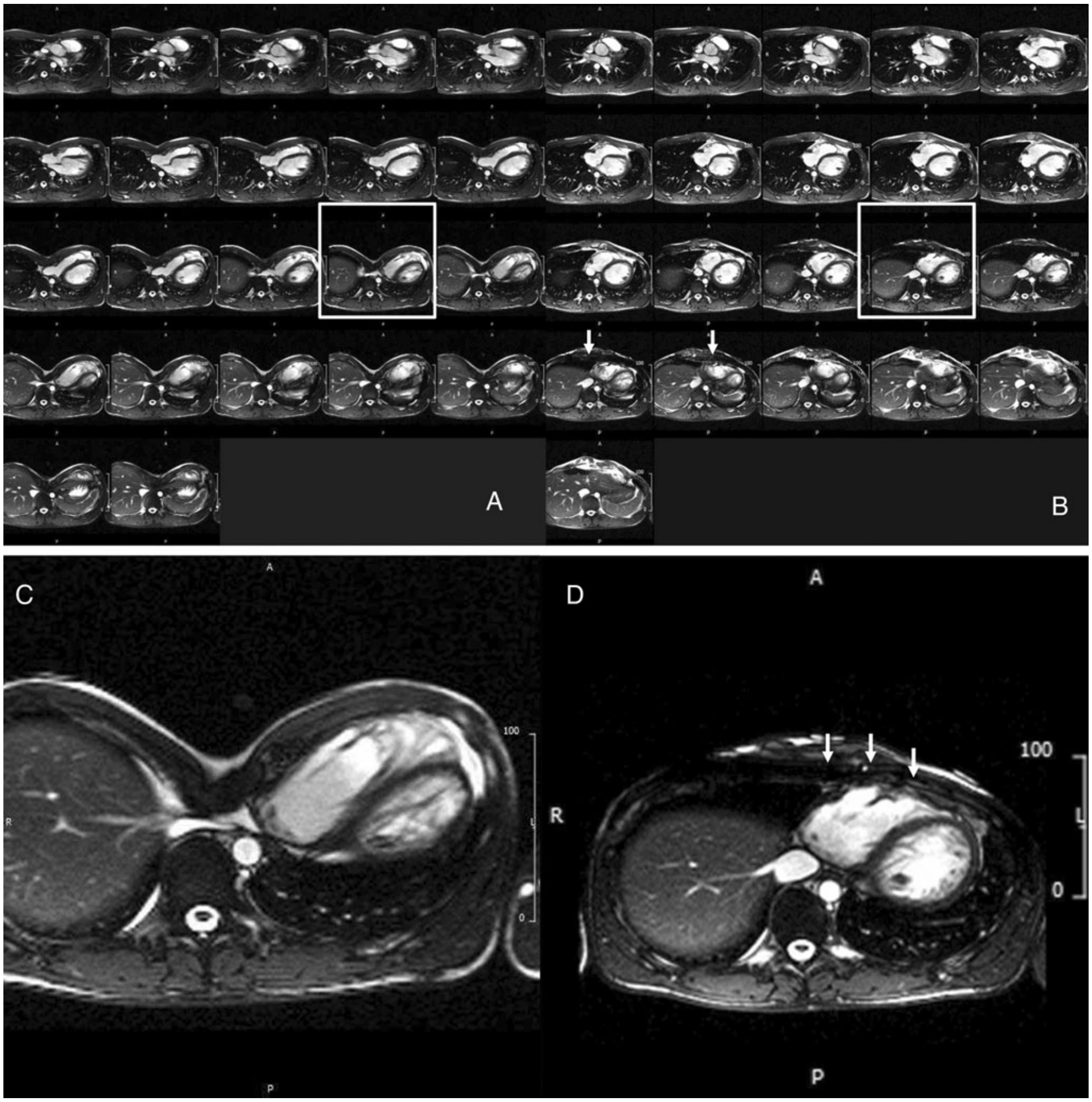


Figure 3: (**A** and **B**) Changes in RV shape observed by CMR illustrated in 1 typical case applying cine images in an axial orientation covering the whole ventricle. RV distortion and compression between the sternum and vertebral column and its resolution at follow-up. (A and B) Miniature view of the whole stack with a white rectangle indicating the representative slices as shown in **C** and **D**. (A and C) Preoperative RV evaluation. (B and D) RV evaluation post-surgery. White arrows in D indicate artefacts due to the titanium bar. RV: right ventricle; CMR: cardiovascular magnetic resonance.

Predictive value of preoperative cardiac function

The preoperative RVEF and LVEF were predictive of postoperative increase in the RVEF. Using only the RVEF at baseline as the predictive parameter, an RVEF of 44.6% could separate patients who reached at least an increase of 4% RVEF with a specificity of 87% (95% CI 66–97%) and a sensitivity of 80% (95% CI 52–96%). When both, preoperative RVEF and LVEF are used as predictive parameters, then the patients who reached at least an increase of 4% RVEF can be detected with 73% sensitivity (95% CI 45–92%) and 96% specificity (95% CI 78%–100%). The ROC curves are shown in Fig. 5. Including the LVEF as a second parameter increases the area under the curve by only 0.0069; however, the specificity is improved at the cost of lower sensitivity.

DISCUSSION

The aim of our study was to explore the impact of surgical correction of PE on cardiac function as the current literature provides inconsistent results [3, 4]. To the best of our knowledge, this is the largest cohort of patients with PE followed with CMR before and after surgical correction. The detailed 3D assessment of cardiac function and its relation to the thoracic anatomy was successful in the majority of patients despite the implanted titanium bars, with good interoberserver variability. The most important findings were that patients in our cohort with PE had a reduced RVEF prior to surgery despite normal LV function. Furthermore, the RVEF improved significantly after successful correction. None of the thoracic indices were predictive of postoperative improvement in the RVEF. A reduced preoperative RVEF could predict the postoperative RVEF recovery.

Cardiac function

Whereas echocardiography is currently the basic tool for the assessment of cardiac function, CMR is the accepted gold standard and offers advantages by detecting subtle differences. Interestingly, due to its low variability and high reproducibility, it was reported

Table 1: Chest and cardiac indices

Variable	Time of assessment		*P*-value
	Preoperative (*n* = 38)	FU3 (*n* = 38)	
Chest indices			
Haller index (T/D)	9.64 (8.18–11.11)	3.00 (2.84–3.16)	<0.0001
Left chest flatness (T/L)	2.07 (2.01–2.13)	1.88 (1.83–1.93)	<0.0001
Right chest flatness (T/R)	2.07 (2.02–2.12)	1.93 (1.88–1.96)	<0.0001
Cardiac indices			
Chest wall asymmetry index (L/R)	1.01 (0.98–1.04)	1.03 (1.02–1.04)	<0.0001
Cardiac compression index (H/M)	3.93 (3.53–4.33)	2.08 (1.98–2.19)	<0.0001
Cardiac asymmetry index (P/M)	2.36 (2.12–2.59)	1.38 (1.33–1.44)	<0.0001
Cardiac left lateral shift (%)	83.4 (80.7–86.2)	78.0 (74.2–81.8)	0.0075

Continuous values are expressed as LS mean (95% CI). The table shows changes in thoracic indices at follow-up 3 (FU3) after surgical correction in comparison with the preoperative stage. All chest and cardiac indices improved, indicating a successful intervention. The indices are also illustrated in Fig. 2.
D: the minimum sternovertebral distance; H: the widest transverse diameter of the heart; L: antero-posterior diameter of the left hemithorax; M: the narrowest antero-posterior diameter of the heart at the xiphoid process; P: the widest paramedian antero-posterior diameter of the heart; R: antero-posterior diameter of the right hemithorax; T: maximum transverse diameter of the chest.

Table 2: Changes in the left and right ventricular function at all time points during follow-up

Variable	Time				*P*-value for change pre versus FU3
	Preoperative	FU1 (13 ± 7 days)	FU2 (120 ± 47 days)	FU3 (472 ± 162 days)	
Patients	*n* = 38	*n* = 27	*n* = 33	*n* = 38	
Heart rate (bpm)	78.1 (73.8–82.4)	75.9 (72.6–79.2)	76.8 (73.8–79.9)	71.2 (68–74)	<0.0001
Right ventricle					
Absolute					
EF (%)	45.7 (43.9–47.4)	51.4 (49.9–52.9)	49.3 (48.0–50.7)	48.3 (46.9–49.5)	0.0004
EDV (ml)	186.6 (172.0–201.3)	178.4 (171.1–185.6)	179.7 (173.0–186.4)	187.1 (180.1–193.3)	0.7590
ESV (ml)	101.5 (92.5–110.4)	82.5 (75.9–89.1)	91.2 (85.1–97.3)	97.2 (91.6–102.8)	0.0718
SV (ml)	85.1 (78.0–92.3)	91.4 (86.7–96.2)	88.5 (84.1–92.8)	90.0 (86.0–94.0)	0.0167
Normalized (BSA)					
EDV (ml/m^2)	103.1 (97.9–108.3)	99.5 (95.1–104.0)	99.8 (95.7–103.8)	101.5 (97.7–105.2)	0.4815
ESV (ml/m^2)	56.1 (52.6–59.6)	48.5 (45.7–51.4)	50.6 (48.0–53.3)	52.7 (50.3–55.1)	0.0168
SV (ml/m^2)	47.1 (44.2–49.9)	50.9 (48.4–53.4)	49.1 (46.9–51.4)	48.8 (46.7–50.9)	0.1028
Normalized (height)					
EDV (ml/cm)	1.04 (0.97–1.1)	1.00 (0.95–1.04)	1.00 (0.96–1.03)	1.03 (1.00–1.07)	0.7718
ESV (ml/cm)	0.57 (0.52–0.61)	0.48 (0.46–0.51)	0.50 (0.48–0.53)	0.54 (0.51–0.56)	0.0253
SV (ml/cm)	0.48 (0.44–0.51)	0.51 (0.49–0.54)	0.49 (0.48–0.52)	0.50 (0.48–0.52)	0.0412
Left ventricle					
Absolute					
EF (%)	61.0 (59.3–62.7)	63.1 (61.4–64.8)	62.9 (61.4–64.4)	62.7 (61.3–64.2)	0.0165
EDV (ml)	142.2 (132.1–152.4)	150.3 (143.9–156.6)	141.3 (135.5–147.1)	146.8 (141.4–152.2)	0.0648
ESV (ml)	55.4 (50.8–60.0)	55.6 (51.9–59.3)	52.6 (49.2–55.9)	55.3 (52.1–58.4)	0.8135
SV (ml)	86.8 (80.1–93.5)	94.5 (90.0–99.0)	88.8 (84.7–92.8)	91.5 (87.7–95.3)	0.0036
Normalized (BSA)					
EDV (ml/m^2)	79.0 (74.9–83.0)	84.1 (80.5–87.7)	78.5 (75.3–81.7)	79.5 (76.5–82.6)	0.5914
ESV (ml/m^2)	30.8 (28.7–32.9)	31.2 (29.1–33.3)	29.3 (27.3–31.2)	29.8 (28.1–31.60)	0.2986
SV (ml/m^2)	48.2 (45.3–51.0)	52.8 (50.5–55.1)	49.3 (47.2–51.3)	49.7 (47.8–51.7)	0.0591
Normalized (height)					
EDV (ml/cm)	0.79 (0.75–0.85)	0.84 (0.80–0.87)	0.78 (0.75–0.82)	0.81 (0.78–0.84)	0.2127
ESV (ml/cm)	0.31 (0.29–0.33)	0.31 (0.29–0.33)	0.29 (0.27–0.31)	0.30 (0.29–0.32)	0.5208
SV (ml/cm)	0.49 (0.45–0.52)	0.53 (0.50–0.55)	0.49 (0.47–0.51)	0.51 (0.49–0.53)	0.0130

Time is expressed as mean (SD); other continuous values are expressed as LS mean (95% CI).
BSA: body surface area; FU: follow-up; EDV: end-diastolic volume; EF: ejection fraction; ESV: end-systolic volume; SV: stroke volume.

to reduce the required sample size for detection of significant volumetric changes when compared with echocardiography. Accordingly, it was applied in interventional trials and in congenital heart diseases with and without surgical correction to quantify LV and RV changes [7]. Similar to our results, Saleh *et al.* [15] reported recently, based on CMR, that 30 patients with PE had a reduced RV function and a normal LV function prior to surgery in comparison with a control group. Using echocardiography, Mocchegiani *et al.* [17] found 20 years ago a reduced RV function on assessing the emptying fraction (FAC) compared with controls. There are a few

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publications comparing both imaging modalities in PE. Recently, Oezcan *et al.* [5] demonstrated abnormalities of the RV when applying echocardiography as well as CMR in 18 patients. They identified discrepancies, but did not identify significant differences. Usually, echocardiographic evaluation of the RV in this anatomically distinct population is based on qualitative assessment or on two-dimensional quantification (e.g. tricuspid annular plane systolic excursion and fractional area change) [17]. But the RV does not follow a geometrical assumption, limiting the accuracy of echocardiographic approaches in PE. This is aggravated by the effect of the thoracic deformity on the substernally located right heart cavities, as shown recently by CMR [5, 15]. Probably, this can explain why only limited data on the impact of surgical repair on RV function exist [18, 19]. There are experiences in 6 patients before and after surgical correction using a sternal eversion method. The authors reported an improvement of LV function, but due to its variability the results regarding RV function were not consistent [20]. By applying echocardiography, Kowalewski *et al.* [19] reported postsurgical improvement of the RVSV when estimating the RV volume by a modified echocardiographic subtraction method. Another group reported an improvement of the RV by applying established parameters, but the RVEF was not given [18]. The increase of RV function was small in our setting, but we were able to show that the RV did not experience worsening. The long-term clinical impact has to be identified during a long-term follow-up. Positive changes in the RVSV and the RVEF are crucial findings and support the previously proposed theory that normalization of thoracic geometry by PE repair may improve the efficiency of diaphragmatic function [21]. The improved ability to generate a negative pulmonary pressure reinforces cardiac stroke volume [2].

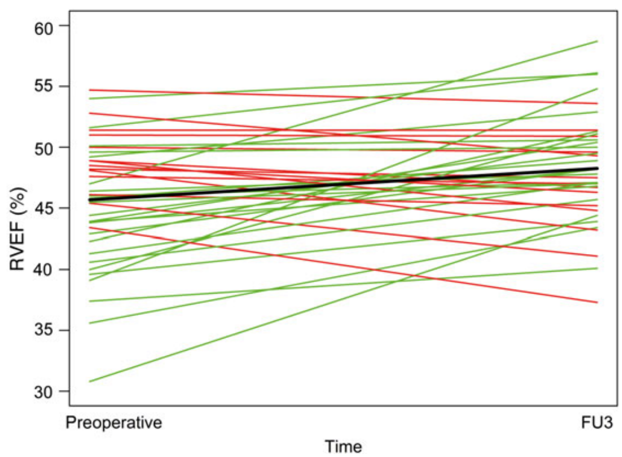

Figure 4: Changes in the right ventricular ejection fraction (RVEF) after surgical correction of pectus excavatum. Line graphs demonstrating the change in RVEF from preoperatively to the last follow-up (FU3). The black line indicates the mean value of the entire group (significant improvement of RVEF, $P = 0.0004$ for preoperative versus FU3).

In our population, the LV function was in the normal range before surgery, but a slight increase during follow-up was detected. Applying echocardiography, various results are published. In a group of 36 patients, changes depended on the severity of deformity [19]. LV function as obtained by M-mode echocardiography was impaired pre- and improved post-surgery in 40 patients [22]. In 2006, a meta-analysis was published showing an increase of cardiac function after surgical repair. But only 11 of the 169 patients experienced the Nuss-based surgical correction as used in our cohort. A minority of the results is based on two-dimensional echocardiography or radionuclide ventriculography [3]. Recently, experience in 6 patients was published applying CMR, showing that normal LV function remains stable after surgery [20]. Patient selection for surgical correction in PE is currently recommended in patients with a severe, symptomatic deformity [9]. Cardiopulmonary impairment may contribute to patients' symptoms in PE, but most of the studies were not able to detect significant differences at rest [23–25]. As a result, the impact of cardiovascular function at rest on the indication for surgery remains unclear. The characteristic of thoracic deformity is one of the most important criteria for surgical repair in PE and it is based on the quantification of different thoracic indices. They describe the deformation and its relation to the heart [13–15].

Predictive value of thoracic indices and cardiac function

Unfortunately, in our cohort, none of the assessed thoracic indices was related to cardiac function or its change after surgery. The question as to how far impaired RV or LV function could be responsible for unfavourable outcome in the natural history of PE is

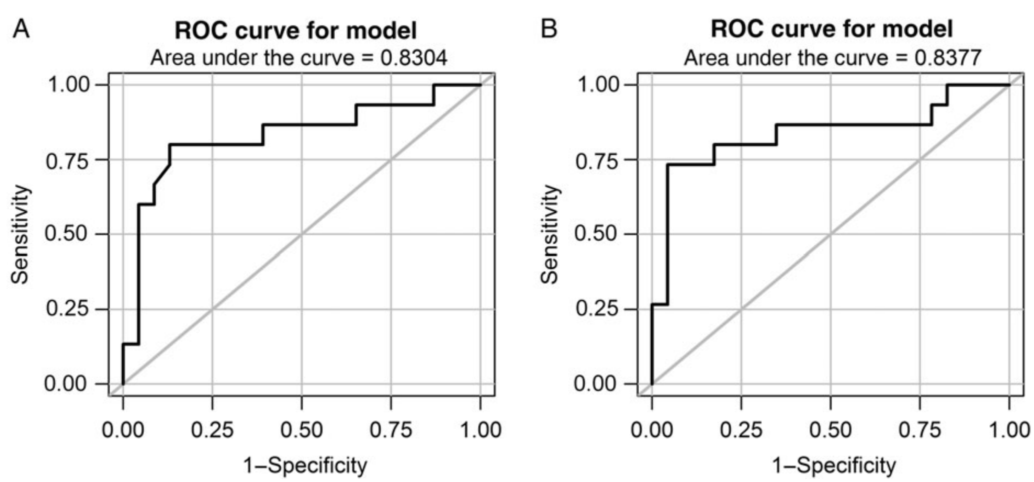

Figure 5: Receiver operating characteristic curves showing a predictive value of preoperative RVEF and LVEF for postoperative increase in the RVEF. (**A**) For postoperative RVEF-recovery a reduced preoperative RVEF (<45%) could predict an increase (at least 3.69%) in postoperative RVEF with 87% specificity (95% CI 66–97%) and 80% sensitivity (95% CI 52–96%). (**B**) Including LVEF as the second parameter increases the area under the curve by only 0.0069. RVEF: right ventricular ejection fraction; LVEF: left ventricular ejection fraction.

scarcely investigated. Therefore, the impact of resting cardiovascular function remains still unanswered. Our finding that the preoperative RVEF is reduced and its reduction seems to predict the post-surgical RV improvement opens a new aspect for preoperative assessment.

The post-surgical improvement of RV function in our cohort is interesting regarding the growing experience that the RV has a prognostic impact in different disorders. Reduced RVEF is predictive of unfavourable outcome in chronic heart failure as well as in pulmonary hypertension [6]. In congenital heart disease, RV function has as a high impact on outcome before and after surgical correction [7]. The data suggest that baseline cardiac function as assessed by 3D CMR could contribute to the decision-making on surgical treatment. The impact on outcome remains currently unanswered and the clinical relevance should be addressed in larger prospective trials.

Limitations

CMR was only performed in patients who received a titanium bar, but also in this case we had to exclude 6 of the patients due to severe imaging artefacts related to the implant. That could cause a selection bias. The study was performed in a single centre. The sample size is relatively small, although this is the largest cohort published in this setting. Long-term follow-up after stainless bar(s) removal would be of high clinical relevance. Due to the setting of the presented analysis, we were not able to show these data in a systematic fashion. These results are of exploratory nature and will serve as the basis for a further prospective trial based on our current findings.

CONCLUSIONS

Our results indicate that cardiac function is stable or improved after successful surgical intervention of PE. By applying 3D CMR, biventricular function could be quantified with high reproducibility. In our population, RVEF was decreased before surgery and improved afterwards. The reduced RVEF was predictive of RVEF improvement after surgery. Our findings underline that the use of CMR gives additional information on pre-surgical evaluation in patients with PE.

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