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Relationship between cardiac MR compression classification and CT chest wall indexes in patients with pectus excavatum

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ABSTRACT

Background/Purpose: In pectus excavatum (PE) patients owing to the location of the heart in the chest cavity, the most affected site of compression by the depressed chest wall is the right heart, and surgical repair has shown to provide a significant relief in the RH cavities compression. Our aim was to explore the relationship between the site of right cardiac compression, chest wall indexes (CT-CWI) and the sternal torsion angle (STA) based on cardiac magnetic resonance (CMR) and computed tomography (CT) among PE patients.
Methods: We included PE patients with no previous surgical correction referred to CMR and chest CT imaging as presurgical evaluations. The following CT-CWI were calculated: Haller Index (HI), correction index (CI) and STA. A CMR compression classification (CMR-CC) was implemented based on the analysis (in the horizontal long axis plane at end of diastole) of the right cardiac compression site, caused by the thoracic cage (sternum/ribs): Type 0 (T0): absence of cardiac compression; Type 1 (T1): compression of the lateral wall of the right ventricle (RV) without involvement of the atrioventricular (AV) groove; Type 2 (T2): compression of the RV involving the AV groove.
Results: Sixty PE patients underwent CMR and chest CT. Fifty (81%) patients were male, and the median age was 17.5 (14.0; 23.0) years. T0, T1 and T2 were found in 14 (23%), 27 (45%) and 19 (32%) patients. There were significant differences between types with regard to the HI (T0 3.9 $\pm$ 1.1, T1 4.8 $\pm$ 2.0, T2 6.4 $\pm$ 3.1, $p < 0.009$) and to the CI (T0 22.1 $\pm$ 10.4%, T1 31.6 $\pm$ 16.1%, T2 46.9 $\pm$ 16.3% $p < 0.0001$) and STA (T0 9.1 $\pm$ 7.9°, T1 12.7 $\pm$ 10.3°, class T2 23.0 $\pm$ 13.6°$p = 0.001$) respectively.
Conclusion: In this study, we established a cardiac magnetic resonance compression classification of patients with pectus excavatum comprising a simple discrimination of cardiac compression sites, which were related to chest wall indexes.
Type of Study: Study of Diagnostic Test.
Level of evidence: Level II.

Pectus excavatum (PE) is the most common congenital chest wall anomaly, affecting 1 in 400 live births. [1] Since most patients with PE are asymptomatic, surgical treatment is generally considered a cosmetic procedure, although a lower quality of life has been demonstrated in these patients based on the significant psychosocial impact particularly among children and young adults [2–4]. In addition, some patients may present symptoms such as exertional dyspnea, fatigue, chest discomfort or palpitations. The compression of the right side of the heart might partly explain the decreased exercise performance that can be occasionally observed among these patients [5, 6]. Furthermore, patients with PE can have significant alterations in cardiac morphology and function that have been recently related to the deformation severity, and that can manifest as an exaggerated interventricular dependence [7].

Computed tomography (CT) chest wall indexes (CT-CWI) such as the Haller index (HI), the Correction Index (CI) and the sternal torsion angle (STA) are currently used to evaluate PE severity and to define and plan the surgical procedure, although these indexes don't account for changes in cardiac morphology [8]. Current decision making of patients with PE involves cardiac deformity indexes, as potentially useful tools to evaluate PE preoperatively and to estimate the result of repair. However, there are no established severity thresholds regarding the extent of cardiac involvement [9]. Sternal rotation might also have an impact in cardiac morphology and function, although this has been not fully elucidated.

Owing to the location of the heart in the chest cavity, the most affected site of compression by the depressed chest wall is the right heart, and surgical repair has shown to provide a significant relief in

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the right heart cavities compression [10]. Cardiac magnetic resonance (CMR) has been established as the reference standard for anatomic and functional cardiac assessment, particularly for the evaluation of the right ventricle (RV) and surrounding structures [11]. The ability of CMR to define the site of maximum heart compression has been published recently [7]. Notwithstanding, to date, there is no evidence linking the different compression sites of the cardiac structure with the CT-CWI in patients with PE.

Accordingly, our aim was to explore the relationship between the site of right cardiac compression, CT-CWI based on CMR and CT among PE patients.

1. Methods

We included consecutive patients with diagnosis of PE and no previous surgical correction referred to CMR and chest CT imaging as presurgical evaluations. Inclusion criteria comprised age > 8 years, and the presence of Haller index ≥3 at cross sectional imaging by CT.

2. Chest CT acquisition

Scans were acquired using a 256-detector CT scanner (ICT; Philips, Cleveland, Ohio, USA). Acquisition parameters were previously reported. [7] Patients were scanned craniocaudally during a full-expiration breath hold [12]. No patients received intravenous contrast material.

3. CMR acquisition

All CMR examinations were performed using a 1.5-T scanner (Achieva, Philips Healthcare, Cleveland, OH), using a 5-element cardiac phased-array coil for signal reception and cardiac synchronization using a vector electrocardiogram at end expiration. Acquisition parameters were described previously. [7] Images were acquired at full-expiration.

4. Definition of CT chest wall indexes (CT-CWI)

All CT studies were analyzed offline in a dedicated workstation (Viewforum; Philips Healthcare) by consensus of two similarly experienced observers (JV and NV, both with more than five years of experience with CT) blinded to the clinical history and CMR data.

5. Haller index (HI)

HI was assessed using two inner chest wall diameters: minimum anteroposterior and a maximum transverse diameter. Both diameters were measured at the point of maximal sternal depression. Using these variables, the HI was calculated from dividing the widest inner transverse diameter of the thoracic cage by the narrowest anteroposterior diameter of the chest wall [13] (Fig. 1.A).

6. Correction Index (CI)

CI corresponds to the percentage of chest depth to be corrected by bar placement. To determine the CI we drew a horizontal line across the anterior spine and measured two distances: the minimum distance between the posterior sternum and the anterior spine and the maximum distance between the line placed on the anterior spine and the inner margin of the most anterior portion of the chest. The difference between these two lines is the amount of defect the patient has in their chest (Fig. 1B) [14].

7. Sternal torsion angle (STA)

STA was calculated in the axial plane considering the angle between the sternum and the horizontal line (Fig. 1C). Torsion measured at an angle more than 30° was defined as severe, whereas lower torsion angles were considered mild [15].

8. CMR analysis and compression classification (CMR-CC)

All CMR studies were analyzed offline in a dedicated workstation (Viewforum; Philips Healthcare) by consensus of two similarly experienced observers (AD and GRG, both with more than eight years of experience with CMR) blinded to the clinical history and CT data. CMR heart compression classification (CMR-CC) was performed based on the analysis of the site of greatest compression of the thoracic cage (sternum/ribs) over the right heart side. The CMR-CC is a visual classification system based on the four-chamber plane. This is the intrinsic transverse cardiac plane, obtained from double oblique angulation of the intrinsic coronal and sagittal cardiac planes. Once this plane was obtained, we evaluated the right heart side in all cross-sectional images at end diastole. The image with maximum right heart side compression was assessed to establish the compression classification.

We based the determination of the AV groove on the visualization of the tricuspid annulus and the right coronary artery that runs through it. Three cross-sectional images of the four-chamber plane were acquired without interslice gap, and visual evaluation of right heart side was performed in all cross-sectional images at end diastole. The image with maximum right heart side compression was assessed to establish the classification. Tricuspid and mitral annulus size was measured at the four-chamber plane at end diastole as the distance from medial to lateral tricuspid and mitral annulus, respectively [16].

The patients were divided into three types. Type 0 (T0) included patients with absence of cardiac compression. Type 1 (T1) included patients with compression of the lateral wall of the RV without involvement of the atrioventricular (AV) groove. Type 2 (T2) comprised patients in whom compression of the thoracic cage compromised the lateral wall of the RV with involvement of the AV groove (Table 1 and Fig. 2).

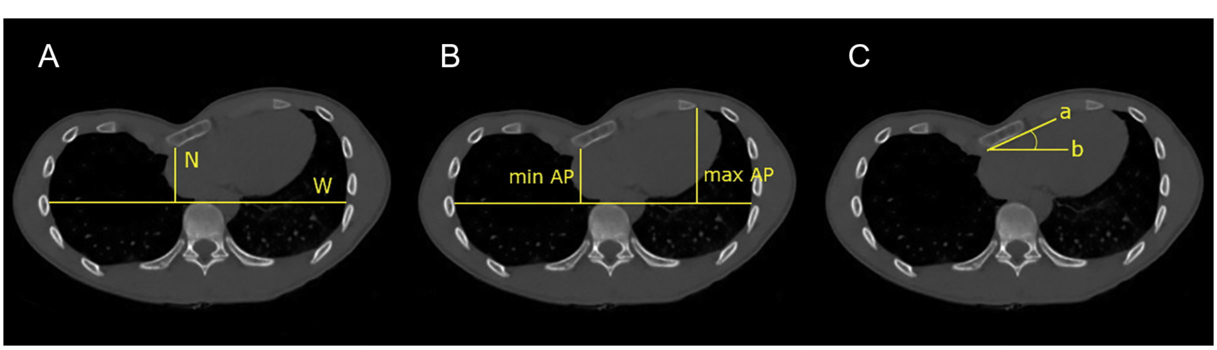

Fig. 1. CT-CWI and STA. A: Haller Index = W/N. B: Correction Index = (Max AP − Min AP/Max AP)*100; Sternal Torsion Angle: angle between line a and b.

Table 1
Cardiac magnetic resonance compression classification (CRM-CC):

Type 0: No right heart side compression.
Type 1: Right ventricle compression.
Type 2: Right ventricle and AV groove compression.
AV: atrioventricular.

This study received institutional research committee approval. Informed consent was obtained from all individual participants included in the study.

9. Statistical analysis

Discrete variables are reported as counts and percentages. Continuous variables are reported as means ± standard deviation and as median (interquartile range), as indicated. Comparisons among groups were performed using one-way analysis of variance. All statistical analyses were performed using SPSS software, version 22.0 (IBM SPSS Statistics for Windows, Armonk, NY). A two-sided $p < 0.05$ indicated statistical significance.

10. Results

Sixty patients with PE underwent CMR and chest CT. Fifty (81%) patients were male, and the median age was 17.5 (14.0; 23.0) years. Patients were classified into 3 types according to the CMR-CC (Table 1). The most frequent site of right heart side compression was the free wall of right ventricle 27 (45%) without compromise of the AV groove (Fig. 2). Both RV and AV groove compressions were found in 19 (32%) patients. There was no RV compression in 14 (23%) patients (2/14 with left side cardiac shift). (Fig. 2).

CMR-CC T2 patients (AV groove compression) showed significantly smaller tricuspid annulus size (CMR-CC T0 32.0 ± 3.0 mm, CMR-CC T1 31.4 ± 4.6 mm, and CMR-CC T2 24.1 ± 4.8 mm $p < 0.0001$) and tricuspid/mitral annulus ratio (CMR-CC T0 0.91 ± 0.1, CMR-CC T1 0.96 ± 0.1, CMR-CC T2 0.75 ± 0.2 < 0.0001) compared to patients without AV groove compression (CMR-CC T0 and T1). Of the 52 patients of whom we had record of symptoms, only 27% showed symptoms of effort in daily life. There were no significant differences in relation to the presence of exertional symptoms among the 3 CMR-CC types (CMR-CC T0 8%, CMR-CC T1 38% and CMR-CC T2 33%, $p = 0.15$).

11. Relationship between the CMR-CC and CT-CWI

CT-CWI were significantly related to the proposed cardiac compression types. There were significant differences between types with regard to the Haller Index (T0 3.9 ± 1.1, T1 4.8 ± 2.0, T2 6.4 ± 3.1, $p < 0.009$) and to the correction index (T0 22.1 ± 10.4%, T1 31.6 ± 16.1%, T2 46.9 ± 16.3% $p < 0.0001$), respectively (Table 2).

An increasing cardiac compression type (compression site progression towards the AV groove) was related to worse sternal torsion angles (T0 9.1 ± 7.9°, T1 12.7 ± 10.3°, T2 22.9 ± 13.6°, $p = 0.001$) (Table 2).

12. Discussion

In the current study involving patients with PE, the site of maximum right heart compression assessed by CMR was related to CT-CWI. More severe indexes have been associated to extension of the compression towards the AV groove. Previous studies using CMR for the assessment of patients with PE have reported distorted RV geometry and reduced RV ejection fraction [17–20]. Evaluation of PE patients with CT attempts to determine the degree of cardiac compression. However, CT cannot determine the functional compromise that can be clearly depicted with echocardiography and CMR [21]. Transthoracic echo four chamber view performed in patients with good acoustic window, enables a clear visualization of any extrinsic compression of the right heart side. However, this is commonly impeded among most PE patients owing to the deformation of the rib cage, leading to a poor visualization of this plane. Unlike transthoracic echo, cardiac MR offers the possibility of obtaining the four-chamber plane in all patients, and without the use of ionizing radiation or contrast, which is particularly important in the evaluation of a young population such as patients with PE. The CMR-CC arises from a modification of the classification previously published by our group [7], allowing a straightforward determination of the presence or absence of cardiac involvement as well as the compression site in a simple way, providing greater applicability in clinical practice. To perform the CMR-CC we used the four-chamber plane at end of diastole. This view allowed us to visualize any extrinsic compression of the right heart from the base to the apex. To establish the relationship between the CMR-CC and the PE severity, we used HI, CI and STA because they represent the degree of severity and the morphology of the chest wall compression and are used by surgeons to define and plan the surgical procedure.

Approximately one quarter of PE patients did not have cardiac compression, being these patients those with the lowest CT-CWI and STA. We found that the extent and location of right heart side compression are closely related to the severity of the CT-CWI. The most affected compression site was the RV, corresponding with the findings of Chu et al. who found RV compression in 52% of PE patients [21]. T1 patients had only mild lateral RV compression while T2 patients had AV groove compromise and showed the most severe CT-CWI and STA owing to the fact that as both increase, the heart is entrapped between the anterior chest and the spine with displacement to the left hemithorax, leading to a greater compression at the basal portion of the heart. It seems that rib cage depression and sternal torsion work together. The increased rib

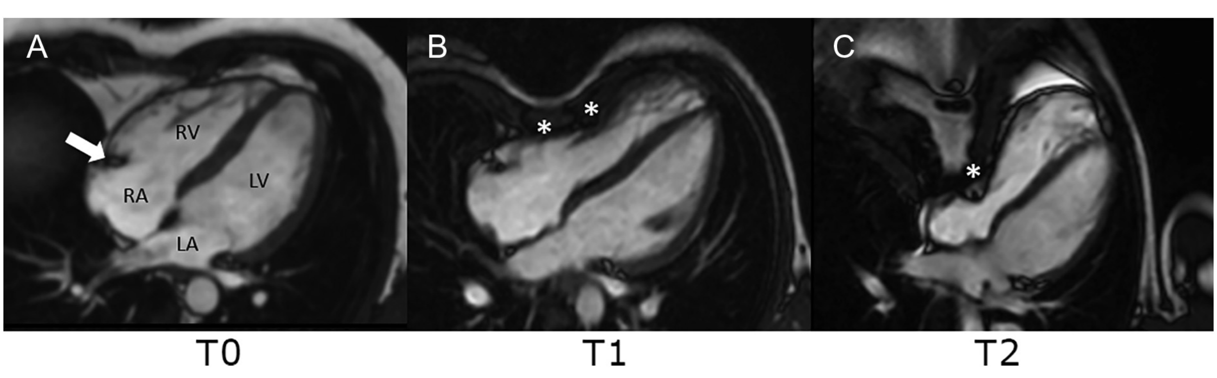

Fig. 2. Balanced steady state free precession horizontal long axis images examples of CMR-CC. A. Type 0 (T0). B: Type 1 (T1). C: Type 2 (T2). RA: Right Atrium. LA: Left atrium. RV: Right ventricle. LV: Left Ventricle. White arrow: Right atrioventricular groove. Asterisk: site of deepest compression.

Table 2
Relationship between CMR right heart site compression types, CT-CWI, and sternal torsion angle.

	Type 0	Type 1	Type 2	p
Haller index	3.9 ± 1.1	4.8 ± 2.0	6.4 ± 3.1	0.009
Correction Index (%)	22.1 ± 10.4	31.6 ± 16.1	46.9 ± 16.3	<0.0001
Sternal Torsion Angle (°)	9.1 ± 7.9	12.7 ± 10.3	22.9 ± 13.6	0.001

cage depression is the main factor for the right heart side compression and displacement of the cardiac structure towards the left hemithorax, while sternal torsion seems to have a greater implication in the location, although it may also contribute to cardiac compression.

The inclusion of the AV groove involvement in the CMR-CC is based on the fact that this structure contains the tricuspid annulus, and its compression has been linked to a certain degree of mild functional tricuspid stenosis that can potentially influence ventricular filling and/or cardiac output [7, 10]. Likewise, the right ventricular outflow tract is located in the upper part of the AV groove. Accordingly, the depression of the chest over such location can sometimes induce a transient cardiac dysfunction when the right heart and pulmonary outflow tract are compressed by the depressed sternum [22]. In keeping with this, Huang et al. demonstrated an immediate significant postoperative improvement in the size of the tricuspid annulus assessed by transesophageal echocardiography. [23] In this same line, Chao et al. studied PE patients who underwent minimally invasive procedure for correction of PE (Nuss surgery) with intraoperative transesophageal echocardiography and found an increase in right atrium, tricuspid annulus, RV outflow tract size, and RV cardiac output after surgery. Likewise, they found that preoperative right atrium and tricuspid annulus size, measured by transesophageal echocardiography, correlated better with preoperative right ventricular stroke volume than to the Haller index [10]. The compression of the RV free wall may also generate the same effect, but since the RV is more distensible than the AV groove, it can expand or move into the left hemithorax in order to maintain the ventricular volumes whereas this is less likely for the tricuspid annulus. It is worth noting that the symptoms are based on what the patients refer to in their daily lives; they were not systematically assessed for exertional symptoms. Therefore, these findings should be considered cautiously. While there was no significant association, it should be noted that PE patients without cardiac compression (CMR-CC T0) had the least exertional symptoms. Patients with PE often describe improvements in exercise stamina following corrective surgery. This improvement could be attributed to improvement in respiratory mechanics and cardiac function. Patients with PE have limited thoracic excursion and an aberrant paradoxical movement of the sternum and abdominal wall during forceful respiration that would limit respiratory function especially in exercise [24]. A recent meta-analysis shows that the improved cardiac function and exercise capacity following correction of PE can be reproduced in the cardiac parameters during exercise. This may be owed to the relief of compressed cardiac chambers with increased anterior–posterior–thoracic dimensions, which again could facilitate an improved filling of the heart. [25] [26], Accordingly, future studies are warranted comparing CMR-CC with pre- and postsurgical intervention cardiopulmonary rest and stress tests focused specially on the RV function in order to place our anatomical findings in clinical perspective [27].

13. Limitations

This study is limited by the relatively small sample size. We do not have CMR follow-up of these patients regarding eventual surgical correction that would allow us to evaluate the modification of the cardiac structure.

14. Conclusions

In this study, we established a cardiac magnetic resonance compression classification of patients with pectus excavatum comprising a simple discrimination of cardiac compression sites, which were related to chest wall indexes.

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