Three-dimensional assessment of pectus excavatum

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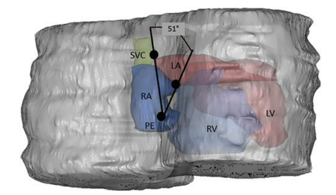

Regression analysis between Index and CPET parameters		
Index	$\dot{V}O2$/kg	O2 Pulse
Compression Angle	R2 0.43, *P* < .001	R2 = 0.39, *P* < .001
Haller Index	R2 = 0.00064, *P* = .9	R2 = 0.059, *P* = .2
Correction Index	R2 = 0.0068, *P* = .7	R2 = 0.001, *P* = .9

The compression angle from superior vena cava to pectus excavatum defect to midatrium.

CENTRAL MESSAGE

The compression angle (superior vena cava to pectus excavatum defect to mid-atrium) may better predict physiological limitation in pectus excavatum than the Haller or correction indexes.

Pectus excavatum (PE) is a common chest-wall deformity, affecting approximately 1 in 300-1000 individuals,[1] with negative physiological and psychological effects.[2] The depressed sternum and ribs can compress the heart and/or lungs, leading to impaired cardiac and/or pulmonary function. Common symptoms include early fatigue, decreased exercise tolerance, shortness of breath, rapid heartbeat, and chest pain. Surgical correction is currently the definitive treatment for PE. Preoperative evaluation consists of imaging and physiologic evaluation with cardiopulmonary exercise testing (CPET).

The Haller index (HI), a 2-dimensional measurement of intrathoracic width and length, is commonly used to assess the severity of PE.[3] However, the HI was developed retrospectively based on 33 patients who underwent surgical repair of PE compared with children without pectus. The HI reflects anatomic severity rather than physiological impact of PE. The most notable other 2-dimensional index is the correction index (CI).[4] The CI was developed to avoid the overlap between patients with PE and control patients without PE. Again, CI is a numerical representation of depth of the defect rather than cardiopulmonary limitation.

The aim of this study is to develop an anatomic measure of PE severity that correlates with physiological limitation. We use data from CPET with a focus on peak oxygen consumption indexed to weight in kilograms ($\dot{V}O_2$/kg) and oxygen pulse (O_2 pulse), as these have been shown to be abnormal in patients with PE and improve postrepair.[5] In addition, we leveraged 3-dimensional (3D) image acquisition to develop novel indices.

PATIENTS AND METHODS

This retrospective study reviewed preoperative data from a consecutive 4-year period. This research was approved by the institutional review board at Phoenix Children's Hospital (institutional review board 15-071, initial approval October 9, 2019). A waiver of consent was obtained for retrospective use of clinical data. Inclusion criteria included patients <18 years who underwent surgical evaluation at Phoenix Children's, availability of 3D imaging with raw data, and a CPET with raw data. Patients with incomplete data were excluded. CPET was performed using an Ultima CPX metabolic cart (Medical Graphics). Exercise values were averaged and expressed as percent predicted using standard equations to facilitate comparison across different demographics. The O_2 pulse served as a surrogate for stroke volume response.

Volumetric, magnetic resonance imaging datasets were used to generate 3D models using Mimics software (Materialise.com). A total of 30 centroid points representing different thoracic, cardiac, and pulmonary structures were created by the investigators using Geomagic Studio software (3Dsystems.com). Procrustes shape analysis was performed to coregister the varying patient sizes for relative distances between indices to be evaluated. The investigators generated 468 novel indices including angular indices (265), triangular projection areas (106), vector differences (61), and relative length-based relationships (36). Univariate regression analysis was performed to evaluate the relationship between indices and CPET variables. An in-house python script was created to perform an automated Procrustes and regression analyses, indices generation (lengths, angles, etc), and identify indices with strongest correlations to CPET.

RESULTS

The study included 26 patients (Table 1) with a male predominance (84%). $\dot{V}O_2$/kg was reduced in 88% of study patients with a reduced stroke volume response in 65%. Regression analysis showed poor correlation between

TABLE 1. Patient demographics and cardiopulmonary exercise testing

Characteristic	Total (26)	Male (22)	Female (4)
Age, y	14.2 (11.6-17.9)	14.1 (11.6-17)	14.8 (13.4-17.9)
Haller index	4.3 (2.8-12.2)	4.3 (3.4-8.5)	5.4 (2.8-12.2)
Correction index	29% (15%-51%)	29% (15%-51%)	22% (20%-39%)
Exercise capacity*	73% (43%-98%)	73% (59%-98%)	69% (43%-83%)
Stroke volume response†	79% (46%-114%)	77% (52%-112%)	89% (46%-114%)

$\dot{V}O_2$/kg, Peak oxygen consumption indexed to weight in kilograms. *Exercise capacity is $\dot{V}O_2$/kg and is reported as percent of predicted. †The oxygen pulse serves as a surrogate for stroke volume response and is reported as a percent of predicted.

$\dot{V}O_2$/kg and HI (R^2 = 0.00064, P = .9) as well as CI (R^2 = 0.0068, P = .7). There were 41 new indices that reached statistical significance in regression analysis with $\dot{V}O_2$/kg (R^2 = 0.15-0.43). The correlation between O_2 pulse and HI (R^2 = 0.059, P = .2) and CI (R^2 = 0.001, P = .9) did not reach significance. Of the new indices, 58 reached statistical significance in regression analysis with O_2 pulse (R^2 = 0.15-0.39). The index generating the highest R^2 with both $\dot{V}O_2$/kg (R^2 = 0.43, P < .001) and O_2 pulse (R^2 = 0.39, P < .001) (Figure 1) was the "compression angle." The compression angle is the angle between the superior vena cava and the maximal point of depression of the PE defect (fulcrum) to the midpoint of the right and left atrium (see Figure 2).

COMMENT

The compression angle had the greatest correlation between the PE imaging and physiologic limitation. Despite the study's limited size, more than 50 3D indices were found to be significant in predicting physiologic impact of PE. We theorize that physiologic limitation in PE occurs due to compression of the heart, inhibiting the right heart in particular from augmenting its stroke volume during exercise. The compression angle describes the proximity of the PE to right heart structures in 3D and thus the degree of compression from the PE. This interaction between the chest wall and the heart is why we theorize that the compression angle and other indices correlate better than the HI and CI. Larger

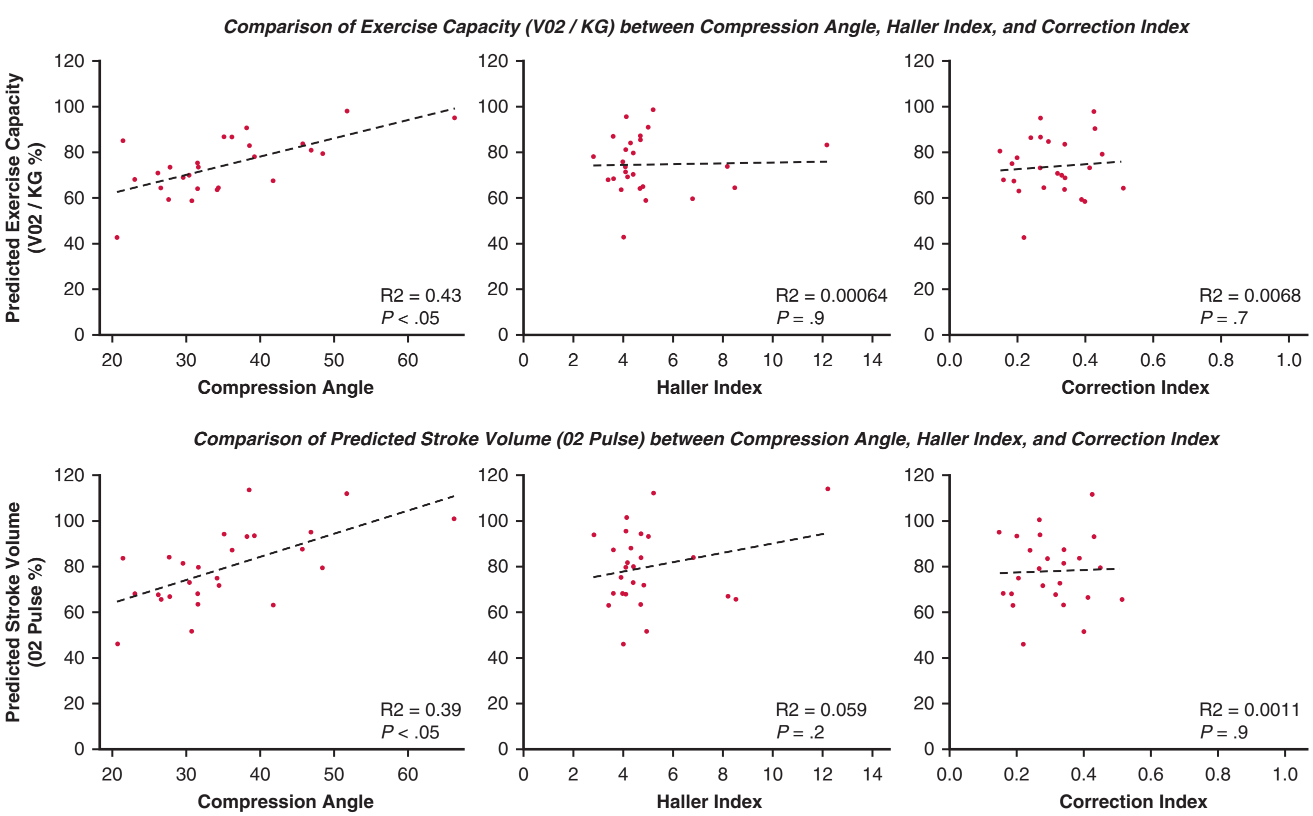

FIGURE 1. Scatter plot and trend lines for regression analysis of exercise capacity and stroke volume response with the compression angle, Haller index, and correction index.

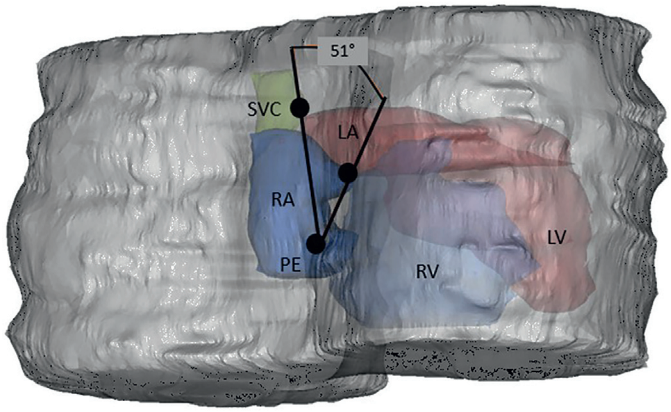

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FIGURE 2. Compression angle: 3-dimensional angle from superior vena cava to pectus excavatum defect (fulcrum) to midatrium. *SVC*, Superior vena cava; *LA*, left atrium; *RA*, right atrium; *PE*, pectus excavatum; *RV*, right ventricle; *LV*, left ventricle; *CPET*, cardiopulmonary exercise testing; $\dot{V}O_2/kg$, peak Oxygen consumption indexed to weight in kilograms; *O2 Pulse*, oxygen pulse.

studies could help determine the clinical utility of novel indices such as the compression angle or other 3D measures in the preoperative evaluation of PE and its anatomic variants.

Conflict of Interest Statement

D.N. is a consultant for KLS and AtriCure and has patents related to pectus repair. All other authors have no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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