A Novel Objective Approach to the External Measurement of Pectus Excavatum Severity by Means of an Optical Device

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Background. **Current approaches to quantifying the severity of pectus excavatum require internal measurements based on cross-sectional imaging. The aim of this study is to exploit a novel index evaluated on the external surface of the chest with a three-dimensional (3D) optical scanner.**

Methods. **Fifty-one children (41 male, 10 female) between 2 and 17 years of age were evaluated with a 3D optical scanner. Pectus excavatum severity was calculated by using an ad hoc instant 3D scanner and defining an automatic procedure to generate an optical 3D correction index (CI3D). For the latter, an ideal threshold was derived from a statistical analysis, and five blind surveys were collected from pediatric specialists on chest wall deformities. The CI3D was then correlated with blind clinical assessments of PE severity.**

Results. **The cutoff thresholds were determined to optimally discriminate between six degrees of severity of PE patients by a correlation analysis. The correlation coefficient obtained by matching the CI3D with the average subjective severity shows that the proposed method outperforms traditional approaches.**

Conclusions. **The optical 3D index has a good match with the average subjective assessment in distinguishing patients with mild to severe PE. This innovative approach offers several advantages over existing indices, as it is repeatable and does not require cross-sectional imaging. The index might be particularly suitable for monitoring the efficacy of nonoperative treatment and, in the future, for designing an optimal personalized usage of therapeutic devices.**

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Pectus excavatum (PE), the most common congenital chest deformity of the anterior thoracic wall, consists of an abnormal growth of the rib cage that manifests itself directly at birth or could develop later, even at puberty. Pectus excavatum leads to a broad variety of clinical conditions ranging from patients with severe cardiopulmonary impairment to those with "simple" cosmetic defects that may cause psychologic distress [1]. Several surgical techniques to treat severe PE deformities have been developed in clinical practice, all of which require a complete evaluation including defect assessment [2, 3]. Furthermore, for those PE patients who are not suitable for surgery and undergo nonoperative treatment (eg, vacuum bell), there is an increasing need to objectively assess its progressive correction. Several so-called "thoracic indices" have been proposed to assess the anatomic defect in a qualitative or quantitative manner [4].

Recently, several approaches have been proposed to assess the chest deformity using optical three-dimensional (3D) body scanners as a convincing radiation-free alternative to computed tomography (CT) scan and magnetic resonance imaging [4–6]. These techniques show promising results in assessing PE severity; however, they require human intervention in the measurement process or, most importantly, they require the patient to stand still for a considerable length of time. A simple, repeatable, and low-cost system that can quickly acquire the patient's chest and evaluate PE severity is, therefore, needed.

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In light of that necessity, this work proposes an innovative method for assessing patient PE severity based on the combination of an optical measurement system with a specifically devised procedure to extract PE-related information. The aims of this study were (1) to develop an index using a 3D optical scanner for the reliable evaluation of PE severity; and (2) to define suitable cutoffs for this index to cluster PE patients according to PE severity.

Material and Methods

Several methods based on thoracic measurements exist to evaluate PE severity. Defined as the ratio of the transverse diameter and the anteroposterior diameter, the Haller index (HI) is traditionally adopted to evaluate the severity of PE and indicate the need for surgical repair (Supplemental Fig 1) [7]. Despite its widespread use in clinical practice, the HI fails to correctly measure the whole population by revealing a dramatic overlap between PE patients and normal control subjects [8, 9]. Moreover, it is highly dependent on chest width and may therefore fail to correctly assess the patient's defect.

To overcome this drawback, St. Peter and associates [8] proposed the correction index (CI). Based on the chest CT/magnetic resonance imaging scan, this index measures the percentage of PE depth that needs to be corrected [8]. As shown in Supplemental Figure 1B, the CI is calculated according to Equation 1:

$$CI = \frac{A - B}{A} \quad (1)$$

where A represents the maximum distance between the line L placed on the anterior spine and the inner margin of the most anterior portion of the chest, and B is the minimum distance between the most posterior point of the sternum and the anterior. Both A and B are evaluated on the slice that contains the greatest sternal depression; this slice is manually selected by clinicians by scrolling through all the tomographic images. Both CI and HI are computed on axial CT or magnetic resonance images; consequently, their use to monitor PE progression is not recommended because of exposure to ionizing radiation or high costs.

As an alternative, optical 3D body scanners have been widely used in the thoracic deformity evaluation field [5, 10–12]. The methods described in the literature are mainly based on several cameras set up to get a full representation of the thorax (chest and back included). For example, some investigators have proposed a 3D scanner mounted on a curved movable platform that rotates 120 degrees from one side to the other, whereas others chose to use a handheld 3D scanner to be manually moved around the patient to obtain the external surface of the thorax [6, 13]. These approaches require the subject to stay still to avoid artifacts from movement. Unfortunately, the pediatric setting imposes the practical constraint of speeding up the entire acquisition process as much as possible owing to the difficulty of getting the child to remain still. We therefore chose to implement a body scanner with a single frontal camera able to acquire the patient's anatomy in less than 1 second.

Methods

This study was carried out within a multidisciplinary collaboration between Meyer Children's Hospital (Italy) and the Department of Industrial Engineering of the University of Florence (Italy). The patients involved in the experimentation were children affected by PE and aged from 2 to 17 years with diagnoses ranging from mild to severe. Consent was obtained from each subject and from a parent or guardian.

Three-Dimensional Optical Scanner

The first step consisted of the acquisition of the patient's chest to create a 3D digital model of the entire chest anatomy. A novel 3D body scanner, including both hardware and software, was created for this purpose, taking advantage of currently available 3D cameras, to enhance the usability of the method even for nonexpert users (ie, medical staff, who do not necessarily need to know the software-related procedures "behind the scenes"). In detail, we developed a 3D body scanner consisting of a single RGB-D (red, green, blue, depth) camera, thus eliminating the need for any manual setup and reducing the acquisition time. The Microsoft Kinect v2 (Microsoft, Redmond, WA) proved to be a sufficiently accurate and affordable sensor and was chosen for integration in the dedicated acquisition system [14, 15].

The patient was placed in the supine position during the 3D acquisition to improve the steadiness of the measurement. Indeed, after a preliminary study of the correct patient pose for index computation, we found that the standing position is not compliant with pediatric PE settings. It is more difficult for a child to stand still than lie still, and to repeat the same pose when standing. Moreover, it is harder for children to stand perfectly perpendicular to a wall, thereby removing a reference plane to be used during index computation.

The patient is asked to lie down on a flat, semirigid mattress that can be considered in the measurement evaluation as the reference plane of the 3D measurement system (ie, the "floor"). To enhance the maximum expression of PE severity, the patient is asked to breath out and hold. The choice to measure the deformity during the expiration phase is based on the results obtained by Birkemeier and associates [16] and Raichura and colleagues [17] because the minimum anteroposterior diameter of the chest decreases in full expiration compared with full inspiration, with a corresponding increase in the pectus indices.

The 3D acquisition device is mounted on a specially devised frame to frontally acquire the patient's chest (Fig 1). Such a frame is designed to allow the vertical translation of the acquisition device; it can therefore be adjusted to scan a wide range of pediatric patients while keeping the acquisition target (ie, the chest) falling within the camera field of view and with sufficient resolution (ie, a range from 0.7 m to 1.2 m).

A software interface was programmed to allow medical staff to easily and safely use the scanner in an outpatient clinical environment. The interface (Fig 1) includes (1)

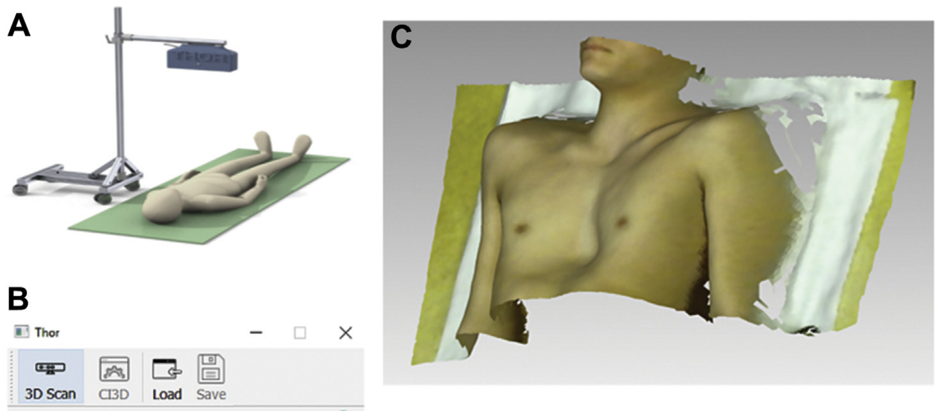

Fig 1. (A) Sketch of the three-dimensional chest scanner for the correction index three-dimensional (CI3D) measurement. (B) Screenshot of the thorax scanner software interface. (C) Three-dimensional (3D) image of a patient for clinical evaluation.

a 3D scan module, which allows the user to proceed with patient chest scanning; (2) a correction index-3D module, which starts the automatic severity index calculation; and (3) a "save" module, which exports the acquired 3D model in a convenient file format (.obj format) together with patient clinical information. A real-time frame stream is provided to the user, thereby allowing correct positioning of the patient before starting the scan by looking at the acquisition area. The scanning process takes less than 1 second; a sound signals the end of acquisition, after which the patient is free to move and the acquired data are processed in the background.

Three-Dimensional Body Scan-Based PE Severity Computation

When the 3D model of the patient chest anatomy is acquired, it is possible to extract the PE-related information from which a new index, called the correction index 3D (CI3D), can be defined as follows:

$$\mathrm{CI3D} = \frac{C - D}{C} = \frac{\Delta}{C} \qquad (2)$$

where C and D are the vertical distances of, respectively, the maximum and minimum sternal depression from the reference plane (as in the semirigid mattress plane), depicted by the line K (Fig 2). This new index is inspired by the CI [8], with the difference that the proposed approach is based on the external surface of the chest.

The following procedure is used to evaluate the CI3D index. First, the reference plane XY (ie, the floor) is automatically identified in the 3D model. Then, a number of equally spaced transverse planes parallel to XZ with a plane-by-plane distance of 1 mm are automatically drafted in the 3D model (Fig 3). The intersection of these planes with the 3D model of the chest allows the determination of a different Δ value for each transversal plane. Among all the Δ values measured on the set of transversal planes, the maximum one is considered as representative of the patient's pathology. Finally, the CI3D index is computed with reference to this plane (Fig 3C), normalizing the difference Δ by the maximum value of that section C and multiplying by 100; as proposed for the original CT-based index, the resulting value indicates the missing height of the chest versus the ideal height of the chest. For the sake of providing a highly available technology and a quick, compact, and user-friendly system, we decided to focus the analysis only on the chest area, not taking into account the back of the patient (ie, the scoliosis).

Severity Clinical Score

A severity clinical score (SCS) was obtained by asking five physicians, expert in the field of thoracic deformities, to blindly evaluate the defect of 51 patients with PE according to the degrees listed in Table 1. For each clinical case, the "ground truth" is the mean value (MSCS) of the five SCS. The standard deviation was also evaluated together with the mean value of SCS for each clinical case. We measured that the standard deviation values

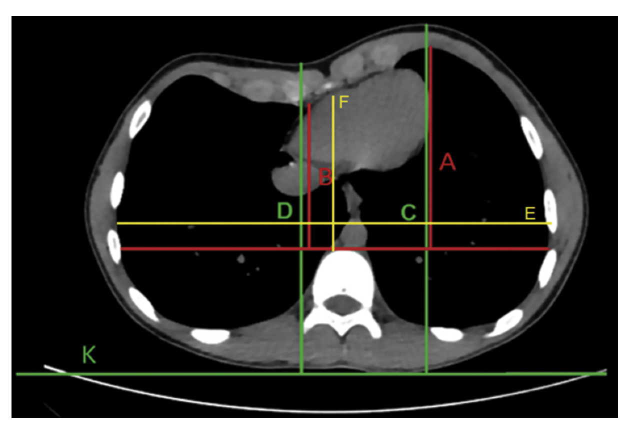

Fig 2. Example of correction index (CI) calculation (red) and corresponding correction index three-dimensional (CI3D) calculation (green): (A) maximum distance between the anterior spine and the inner margin of the most anterior portion of the chest; (B) minimum distance between the most posterior point of the sternum and the anterior; (C) maximum distance between the outer margin of sternal depression and the reference plane; (D) minimum distance between the outer margin of sternal depression and the reference plane; (E) horizontal reference line for measuring Haller Index; (F) vertical reference line for measuring Haller Index.

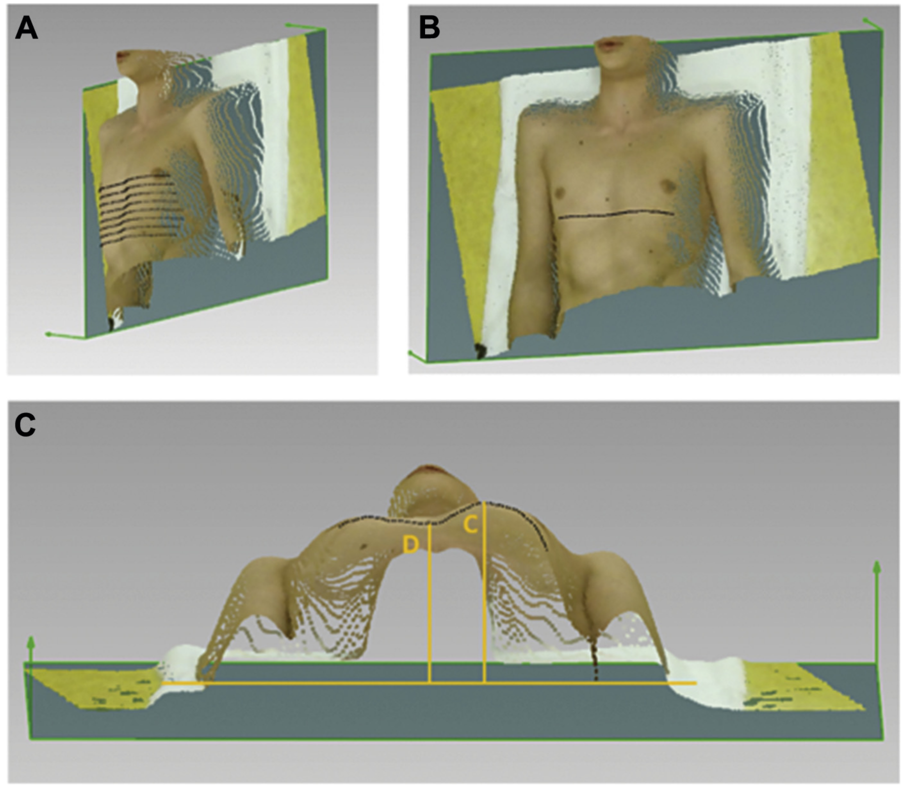

Fig 3. (A) Sheaf of planes perpendicular to the ground cutting the chest. (B) Slice containing the larger excursion automatically identified by the software. (C) Computation of the distances C and D in the three-dimensional model.

ranged from 0 to 1.2, with a mean standard deviation among all cases of 0.7. The CI3D values have been mapped to six severity levels. This classification allows a better discrimination of different cases with respect to the basic severity levels (mild, moderate, and severe) and provides a strong validation of the proposed method.

Data Analysis

To prove the effectiveness of the proposed index, the CI3D calculated for a set of patients was compared with the SCS. In particular, to validate the CI3D measure as an objective PE severity indicator, and therefore to determine the severity class boundaries, we chose the Jenks natural breaks classification [18], an iterative clustering algorithm that computes the thresholds that better separate the data cluster by reducing the variance within classes and maximize the variance between classes. Subsequently, to define the precision of the classification, an attribute agreement analysis (Kendall coefficient) was performed to assess the agreement between the rating of our system and the clinical classification [19].

The statistical analysis to compare the computed CI3D values and the SCS was carried out using a scatter plot, and the Pearson correlation analysis and the attribute agreement analysis of the index classification was performed with the Minitab 18 software (Minitab, State College, PA) [20]. All values were considered significant if p less than 0.05.

Table 1. Values of Severity for Clinical Assessment

0	Absent
1	Mild
2	Moderate
3	Moderate to severe
4	Severe
5	Extremely severe

Results

Fifty-one patients (41 male, 10 female) diagnosed with mild to extremely severe PE, aged from 2 to 17 years,

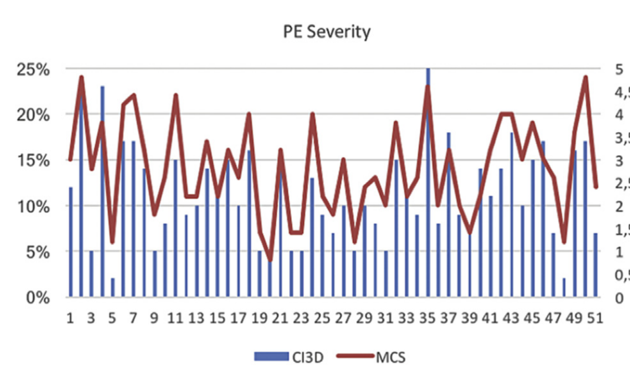

Fig 4. Pectus excavatum (PE) severity according to mean clinical severity (red) score as in Table 1, and the proposed correction index three-dimensional (blue) of the 51 sampled patients. (CI3D = correction index three-dimensional; MCS = mean clinical severity score.)

Table 2. Correction Index Three-Dimensional Values Calculated on 51 Patients With Corresponding Values of Mean Severity Clinical Score and Standard Deviation of Severity Clinical Score

Pt. No.	CI3D	MSCS	SSCS	Pt. No.	CI3D	MSCS	SSCS	Pt. No.	CI3D	MSCS	SSCS
1	12%	3	0.00	19	5%	1.4	0.89	37	18%	3.2	0.84
2	23%	4.8	0.45	20	5%	0.8	0.84	38	9%	2	1.22
3	5%	2.9	0.55	21	16%	3.4	0.42	39	7%	1.4	0.89
4	23%	3.8	0.45	22	5%	1.4	0.55	40	14%	2.2	1.10
5	2%	1.2	0.45	23	5%	1.4	0.89	41	11%	3.2	0.84
6	17%	4.2	0.45	24	13%	3.9	0.74	42	14%	4	0.00
7	17%	4.4	0.55	25	9%	2.2	0.45	43	18%	3.9	0.22
8	14%	3.2	1.10	26	7%	1.8	0.45	44	10%	2.9	0.22
9	5%	1.8	0.84	27	10%	2.9	0.74	45	15%	3.8	0.84
10	8%	2.6	0.89	28	5%	1.2	1.10	46	17%	3.1	0.74
11	15%	4.4	0.55	29	10%	2.4	0.89	47	7%	2.6	0.55
12	9%	2.2	0.45	30	8%	2.6	0.89	48	2%	1.2	0.84
13	10%	2.2	0.84	31	5%	2	1.22	49	16%	3.7	1.20
14	14%	3.4	0.89	32	15%	3.8	0.84	50	17%	4.8	0.45
15	11%	2.2	1.10	33	11%	2.2	0.45	51	7%	2.5	0.50
16	15%	3.2	1.10	34	9%	2.6	0.89				
17	10%	2.6	0.89	35	25%	4.6	0.55				
18	16%	4	0.71	36	8%	1.9	0.74				

CI3D = correction index three-dimensional; MSCS = mean severity clinical score; Pt. No. = patient number; SSCS = standard deviation of severity clinical score.

were studied. Figure 4 shows the histogram of the collected CI3D values and the line representing the SCS of the same patients; the numerical values are in Table 2.

To demonstrate that the acquisition system allows a precise representation of the external geometry of the chest, the CI3D index was evaluated on a subset of 4 patients using both the 3D scanner and a CT scan. Although limited to a small number of patients, results of this comparison (Table 3) show that the optical system spatial resolution is sufficient to deliver a reliable CI3D index. The calculated CI3D values were used as independent variables to be correlated with the SCS for each patient. A positive correlation between variables is depicted in Figure 5B and shows a linear relationship between CI3D and the clinical assessments, indicating a good accuracy. A least-squares regression line predicting the clinical diagnosis from the evaluated CI3D values is also reported in Figure 5B.

Table 3. Comparison Between Correction Index Three-Dimensional Values Computed on Data Acquired With Proposed Body Scanner and Values Computed on Three-Dimensional Reconstruction From Computed Tomography Scans

Pt. No.	CI3D Scan	CI3D CT
1	25%	24%
2	10%	9%
3	16%	15%
4	19%	20%

CI3D = correction index three-dimensional; CT = computed tomography; Pt. No. = patient number.

The null hypothesis was formulated as the lack of correlation between CI3D values and SCS values, and the correlation was tested with the Pearson coefficient at a significance level of $\alpha = 0.05$. As a result, a correlation coefficient of 0.87 was obtained and because of a p value less than 0.05, the hypothesis of no correlation was rejected, indicating that CI3D is a good candidate to appropriately represent PE severity.

The five thresholds represented in a map between six severity classes (absent to extremely severe defect) and CI3D values are shown in Figure 5A according to the Jenks natural breaks classification method. The classification was compared with the SCS values to determine the strength of the CI3D when coupled with the chosen classifier. An attribute agreement analysis was performed to measure the percentage of agreement between the appraisal (the CI3D values) and the actual standard (SCS).

Kendall's correlation coefficient was also evaluated to consider the magnitude of agreement/disagreement as well; the percentage score is 64.71% and Kendall's correlation coefficient is 80% with a p value less than 0.05, indicating that agreement exists between the appraisers and the standard [21]. Furthermore, the results performed by separating the male group from the female group show no significant differences, with $\rho_{male} = 0.87$ and $\rho_{female} = 0.89$.

Comment

This work proposes an innovative measure of PE severity, the CI3D, which calculates a 3D version of the correction index in line with the current trend toward a noninvasive

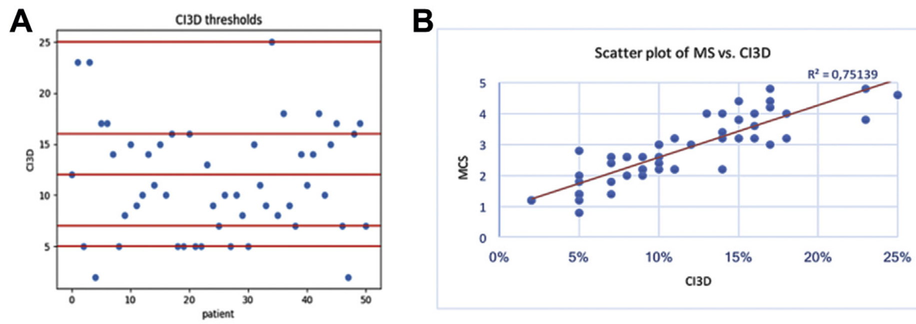

Fig 5. (A) Correction index three-dimensional (CI3D) values of 51 patients (blue dots) and the five thresholds produced by the Jenks natural breaks classification (red lines). (B) Scatter plot and regression line of CI3D values and the mean clinical severity score (MCS) show a positive correlation between the two. (MS = mean score; vs. = versus.)

evaluation of chest deformities. The method is particularly useful for application in the pediatric setting (although it is also applicable to adults), and is not intended to replace cross-sectional imaging nor to measure the same skeletal depression but, rather, to introduce a safe, low cost, and easy to use system. The skin surface can introduce a source of error; nevertheless, when the subcutaneous fat or muscle tissue is limited, as for most patients affected by PE, the system still maps the CI3D value in the correct severity class [22]. The CI3D index is automatically evaluated using the proposed device and software achieving an optimal trade-off between low acquisition time and reduced cost.

The CI3D data were extracted from 51 patients and analyzed by comparing them with their PE clinical severity evaluation, herein considered as the "ground truth." The correlation between CI3D values and clinical diagnosis was significant.

To translate CI3D values into natural numbers describing PE severity as depicted in Table 1, a classification method has been applied to detect the optimal threshold values so that they can be compared with SCS values. The CI3D values reached approximately 65% of matches, values that showed a positive correlation confirmed by Kendall's coefficient. These results are promising, especially if we consider that the clinical assessment is not trivial; indeed, the overall judgment includes a number of clinical factors not necessarily localized in the proximity of the defect but, rather, an overall evaluation of the global aesthetic appearance of the chest. The physician evaluations can differ significantly from one to another, hence the mismatch between CI3D and SCS; in particular, SCS might be influenced by other geometrical properties of the chest such as asymmetry or eccentricity. Future work should consider these anatomic variations, with the final aim of better matching automatically extracted parameters and clinical judgment by implementing other 3D scan-based indices.

Although the CI3D index is inspired by the widely recognized CI index, the assessment of a complete comparison of the trends for the two indices would impose the use of tomographic imaging on the set of 51 patients involved in the experimentation. That would clash with the choice to propose a low cost and completely radiation-free method. However, because a few CT scans are available, as shown in Table 3, a qualitative comparison between CI3D, CI, HI, and clinical diagnosis can be assessed. The results of this comparison, depicted in Table 4, show that the CI3D, CI, and HI indices had high values on the four examined patients, corresponding to an SCS greater than 3. In particular, the HI index exceeds the value of 3.25 in 2 cases. For the same cases, the CI3D classification leads to a severe PE (grade 4).

The CI3D may be particularly useful for the repeated evaluation of PE patients who undergo conservative treatment (ie, vacuum bell, physiotherapy, and so forth) and for the postoperative evaluation of the correction obtained in PE patients. When the patient is following a nonsurgical treatment path, the CI3D index can be used to monitor progression and to provide personalized indications regarding the timing and frequency of device applications. The CI3D could also be exploited in patients who might require subsequent surgical refinement at bar removal [23].

As a future perspective, PE severity assessed with a consistent optical index together with maximal cardiopulmonary function might lead to the definition of a reliable cutoff for the surgical selection of patients to whom an operative treatment should be offered. To further validate the measurement technique for CI3D and to better interpret this new methodology compared with more traditional measures, the authors aim to carry out in the near future a multicenter study with other institutions willing to use both the devised

Table 4. Comparison Between Correction Index Three-Dimensional, Correction Index, and Haller Index Values Computed on Four Patients With Available Computed Tomography Scans

Pt. No.	CI3D	CI	HI	MSCS	CI3D Classification
1	25%	46.7%	4.46	4	4
2	10%	28.9%	2.85	3	3
3	16%	29.4%	3.18	3	3
4	19%	31.6%	4.03	4	4

CI = correction index; CI3D = correction index three-dimensional; HI = Haller Index; MSCS = mean severity clinical score; Pt. No. = patient number.

hardware and software. In particular, as soon as more CT scans are available from multiple pediatric centers we could further validate the correctness of optical-based measurement and, possibly, introduce a new measurement standard by gradually reducing the use of CT, at least for noncritical PE.

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