Original Article

Comparison of cardiovascular metrics on computed tomography pulmonary angiography of the updated and old diagnostic criteria for pulmonary hypertension in patients with chronic thromboembolic pulmonary hypertension

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Background: In the 2022 European Society of Cardiology (ESC) and the European Respiratory Society (ERS) guidelines, the diagnostic criteria for pulmonary hypertension (PH) included a reduced mean pulmonary artery pressure (mPAP) of 20 mmHg (mPAP >20 mmHg). This study aimed to reassess cardiovascular metrics on computed tomography pulmonary angiography (CTPA) for chronic thromboembolic pulmonary hypertension (CTEPH) to optimize the timely diagnosis of patients with suspected PH.

Methods: Patients with suspected CTEPH who underwent CTPA and right heart catheterization (RHC) between January 2019 and December 2022 in China-Japan Friendship Hospital were retrospectively included. They were grouped into CTEPH and non-PH groups according to the new and old criteria (2022 and 2015 ESC/ERS guidelines) for the diagnosis of PH. Cardiovascular metrics including the main pulmonary artery diameter (MPAd), Cobb angle, and right ventricular free wall thickness (RVWT), among others, were measured. The correlation of these metrics with hemodynamic data was analyzed with Spearman rank correlation analysis, while the differences in cardiovascular metrics between the updated (mPAP >20 mmHg) and old PH criteria (mPAP ≥25 mmHg) were compared with independent samples *t*-test or the Mann-Whitney test. Receiver operator characteristic (ROC) curve analysis was performed for the prediction model.

Results: The study enrolled 180 patients (males n=86; age 55.5±12.0 years old). According to the old guidelines, 119 patients were placed into the PH group (mPAP ≥25 mmHg) , while according to the new

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guidelines, 130 patients were placed into the PH group (mPAP >20 mmHg). Cardiovascular metrics on CTPA between the updated and old guidelines were comparable (P>0.05). Compared to other metrics, an MPAd of 30.4 mm exhibited the highest area under the curve (AUC: 0.934±0.021), with a sensitivity of 0.88 and specificity of 0.90. MPAd [odds ratio (OR) =1.271], transverse diameter of the right ventricle (RVtd; OR =1.176), Cobb angle (OR =1.108), and RVWT (OR =3.655) were independent factors for diagnosing CTEPH (P<0.05). Cobb angle, right and left ventricular transverse diameter ratio, and right and left ventricular area ratio moderately correlated with mPAP (r=0.586, r=0.583, r=0.629) and pulmonary vascular resistance (PVR) (r=0.613, r=0.593, r=0.642).

Conclusions: Cardiovascular metrics on CTPA were comparable between the new and old guidelines for CTEPH diagnosis. Cardiovascular metrics on CTPA can noninvasively assess the hemodynamics of patients with CTEPH.

Keywords: Pulmonary hypertension (PH); chronic thromboembolic pulmonary hypertension (CTEPH); computed tomography pulmonary angiography (CTPA); hemodynamics

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Introduction

Chronic thromboembolic pulmonary hypertension (CTEPH) is a common and important cause of pulmonary hypertension (PH). It is characterized by pulmonary artery occlusion from organized thromboembolic material, causing progressive elevation of pulmonary vascular resistance (PVR) and mean pulmonary artery pressure (mPAP) (1,2). Over time, this pathological process can culminate in right heart failure and even death (1,2). CTEPH can be near-cured with pulmonary endarterectomy (PEA), balloon pulmonary angioplasty (BPA), and medical treatment (1). However, its nonspecific symptoms during the early stage cause a median diagnostic delay of 14 months from the onset of symptoms (3). Computed tomography pulmonary angiography (CTPA) is widely employed for the assessment in CTEPH, and an increased main pulmonary artery diameter (MPAd) and the ratio of MPAd and ascending aorta diameter (MPAd/AAd) along with right heart enlargement on CTPA may indicate the presence of PH (4-18).

In the 2015 European Society of Cardiology (ESC) and the European Respiratory Society (ERS) guidelines, mPAP and PVR for the diagnosis of PH were defined as ≥25 mmHg and ≥3 Wood units (WU), respectively (2,19), a standard that has long been used in clinical work and research. In 2022, the ESC and ERS updated the hemodynamics of PH by lowering the thresholds for mPAP and PVR in healthy individuals to 20 mmHg and 2 WU, respectively (1). This aims to enable patients with suspected PH to receive a timely diagnosis. A meta-analysis reported CTPA had high sensitivity and specificity in the detection of CTEPH when evaluated by expert radiologists (16). However, at present, no research has been conducted to investigate whether the threshold of cardiovascular metrics on CTPA for diagnosing PH is affected by changes in diagnostic criteria. Thus, we aimed to compare cardiovascular metrics on CTPA in the prediction of PH under the updated and old criteria and to reevaluate the metrics that are capable of detecting PH in patients at the early stage of CTEPH. We present this article in accordance with the STROBE reporting checklist (available at https://qims.amegroups.com/article/view/10.21037/qims-23-250/rc).

Methods

Population and study design

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013) and was approved by the Institutional Ethics Board of China-Japan Friendship Hospital (No. 2022-KY-048). Individual consent for this retrospective analysis was waived.

For this investigation, 685 participants who underwent right heart catheterization (RHC) between January 2019 and December 2022 were identified from the China-Japan Friendship Hospital. *Figure 1* illustrates the process of selecting participants who had CTPA with fully visible lung

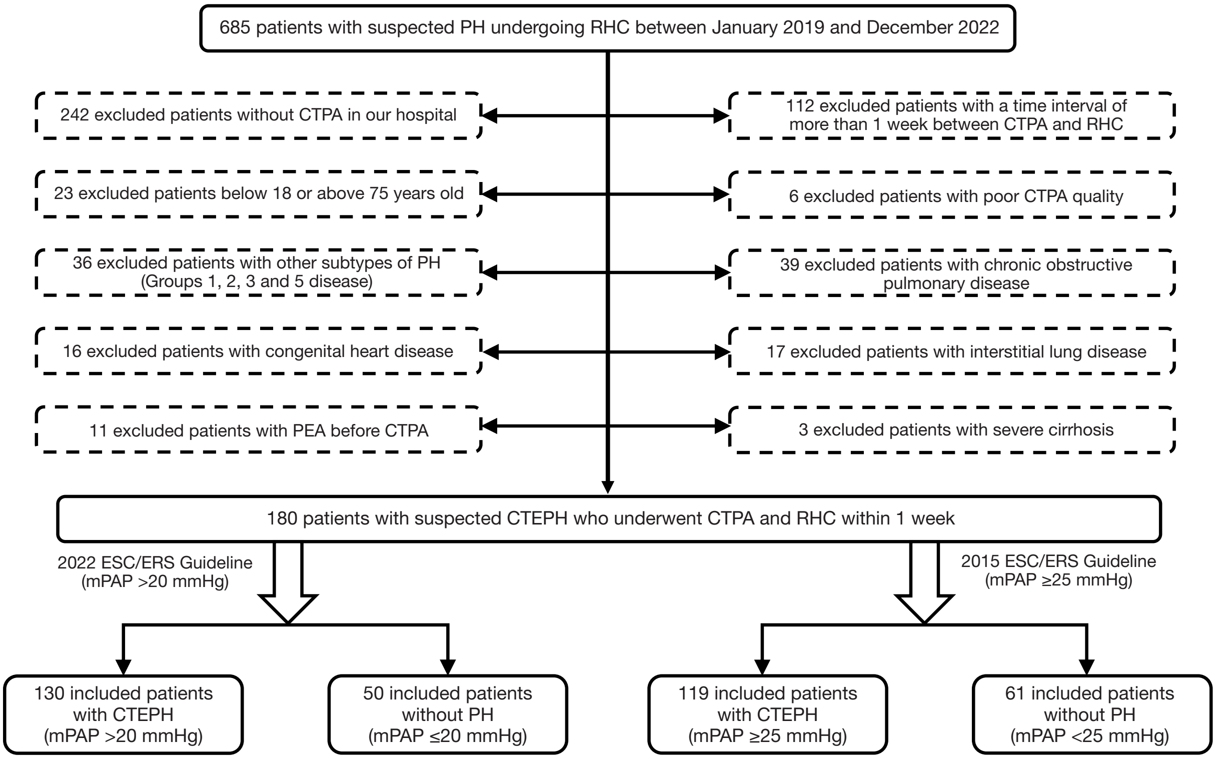

Figure 1 Flowchart detailing participant selection. PH, pulmonary hypertension; RHC, right heart catheterization; CTEPH, chronic thromboembolic PH; CTPA, computed tomography pulmonary angiography; PEA, pulmonary endarterectomy; ESC, European Society of Cardiology; ERS, European Respiratory Society; mPAP, mean pulmonary arterial pressure.

fields within 1 week after RHC. From this group, 4 cohorts were formed based on the 2015 ESC/ERS guidelines (old) and 2022 ESC/ERS guidelines (updated), and included patients were respectively divided into the following groups: CTEPH patients with mPAP >20 mmHg and control patients with mPAP ≤20 mmHg; and CTEPH patients with mPAP ≥25 mmHg and control patients with mPAP <25 mmHg.

The exclusion criteria were as follows: (I) patients younger than 18 years old or older than 75 years old; (II) patients without CTPA or with poor CTPA quality or incomplete RHC data in our hospital; (III) patients with evidence of chronic obstructive pulmonary disease or interstitial lung; (IV) patients with congenital heart disease or severe cirrhosis; and (V) patients who had undergone PEA before CTPA.

CTPA scan protocol

All patients underwent supine CTPA imaging with either a 256-row CT (GE Revolution CT, GE HealthCare, Chicago, IL, USA) or a 320-row CT (Aquilion ONE, Canon Medical Systems, Otawara, Japan) at the end of expiration, with the lung base to apex being covered. The specific scan parameters for the GE Revolution CT were as follows: a tube rotation speed of 0.28 s/rotation; tube voltage determined via kilovolt (KV) intelligent decision technology (KV assist; 100 and 120 KV), tube current determined via 3D automatic tube current modulation (Smart-milliampere), a pitch of 0.992:1, the slices × collimator width is 256×0.625 mm, and a reconstruction image slice thickness and spacing of 0.625 mm. Meanwhile, the specific scan parameters for the Aquilion ONE were as follows: a tube rotation speed of 0.35 s/rotation, a tube voltage of 120 kVp, a tube current determined via automatic tube current modulation, the Slices × collimator width is 320×0.5 mm, and a reconstruction image slice thickness and spacing of 0.5 mm.

A high-pressure injector was used to administer either iodinated contrast agents (350 mg I/mL) or iodopropamide (370 mg I/mL) through the antebrachial vein. A double-barrel syringe containing contrast agent and saline solution

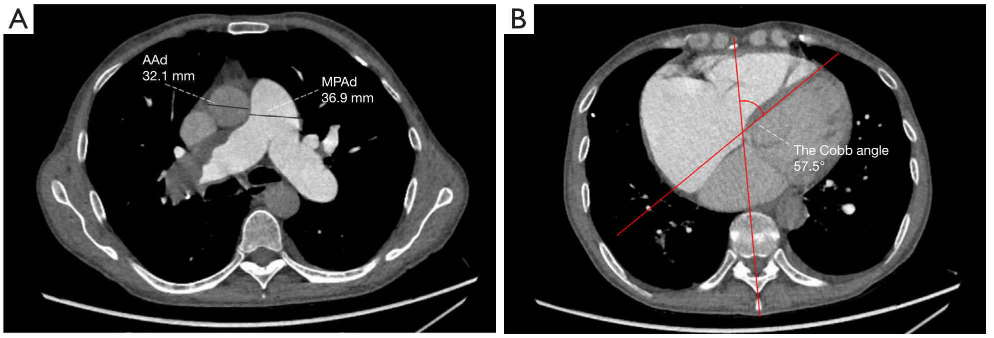

Figure 2 The vascular diameters and Cobb angle measurement from transversal computed tomography pulmonary angiography images. (A) The widest MPAd and the widest AAd at the same level were measured at standard axial images. (B) The Cobb angle, the angle between the interventricular septum and the line connecting the midpoint of the sternum and the thoracic vertebral spinous process, was measured during diastole in the transversal image. MPAd, diameter of the main pulmonary artery; AAd, diameter of the ascending aorta.

was used, with a flow rate of 5 mL/s, a total contrast agent volume of 60–75 mL, and 30 mL of saline solution. The contrast agent detection method used was automatically triggered, with a trigger threshold of 80 Hounsfield units (HU) in the main pulmonary artery.

RHC

All patients underwent RHC through the right internal jugular or femoral vein with a 6F Swan-Ganz thermodilution catheter (Bioptimal International, Tokyo, Japan). Hemodynamic data, including mPAP, ratio of systolic to diastolic PAP (sPAP/dPAP), mean right atrial pressure (mRAP), mean pulmonary artery wedge pressure (PAWP), ratio of systolic to diastolic blood pressure (sBP/dBP), cardiac output (CO), and cardiac index were obtained during the procedure. PVR was calculated using the following formula (20): PVR = (mPAP – mean PAWP)/CO WU.

Image analysis

Two radiologists with 5 years of experience in chest imaging measured the cardiovascular metrics on CTPA and reached a consensus, with discussion being used to resolve any differences. On the transversal images of CTPA (*Figure 2A*), the widest diameter of the main pulmonary artery (MPAd) and the widest diameter of the ascending aorta (AAd) at the same level were measured. The Cobb angle (*Figure 2B*) was considered to be the rotation angle between the interventricular septum and the line connecting the midpoint of the sternum and the thoracic vertebral spinous process. Meanwhile, a radiologist with 15 years of experience completed multiplane reconstruction and measured the following: the longest longitudinal diameter of the right ventricle (RVld); the longest longitudinal diameter of the left ventricle (LVld); the transverse diameter of the right ventricle (RVtd); the transverse diameter of left ventricle (LVtd) (*Figure 3A*); the longest longitudinal diameter of the right atrium (RAld) and the transverse diameter of the right atrium (RAtd) (*Figure 3A*); the longest anteroposterior dimension of the left atrium (LAap) (*Figure 3B*); the widest left-right dimension of the left atrium (LAlr) (*Figure 3B*); and the maximum area of the right ventricle (RVa), left ventricle (LVa), right atrium (RAa), and left atrium (LAa) (*Figure 3C*) on 4-chamber views. The right ventricular free wall thickness (RVWT) and interventricular septal thickness (IVST) at CTPA sagittal position images are also measured and shown in *Figure 4*. The final measurement result was the average of 3 repeated measurements.

Statistical analysis

Statistical analysis was performed using IBM 27.0 (IBM Corp., Armonk, NY, USA). The Kolmogorov-Smirnov test and Shapiro-Wilks test were used to assess the normality of the variables. Normal data are expressed as mean ± standard deviation (SD), and the independent samples *t*-test was used for comparison in different groups. Nonnormal data are expressed as the median [interquartile range (IQR)], and the Mann-Whitney test was used for multiple comparisons among 3 groups. Count data are expressed as frequency

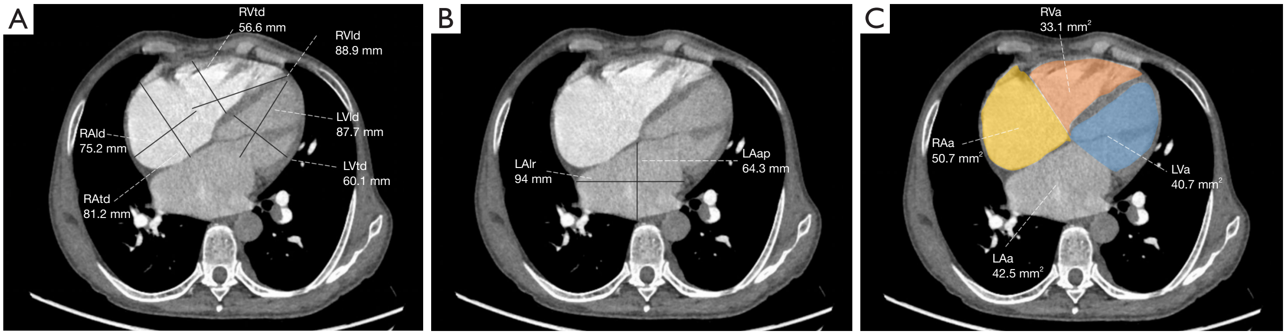

Figure 3 Measurements of the diameters and areas in 4-chamber-view computed tomography pulmonary angiography. (A) The longest longitudinal and transverse diameters of the biventricles and right atrium are illustrated for reformatted 4-chamber views. The transverse axis is parallel to the line connecting the heart valves. The ventricle longitudinal line is the midpoint of the heart valve and the line connecting the apex of the heart, and the right atrium longitudinal line is perpendicular to the transverse axis. (B) The longest LAap and the widest LAlr are illustrated for reformatted 4-chamber views. The LAap is the largest straight-line distance connecting the front and back walls of the left atrium, and the LAlr is perpendicular to the LAap. (C) The maximum 4-chamber heart area was measured on the reformatted 4-chamber position. RVtd, transverse diameter of the right ventricle; LVtd, transverse diameter of the left ventricle; RVld, longitudinal diameter of the right ventricle; LVld, longitudinal diameter of the left ventricle; RAld, longitudinal diameter of the right atrium; RAtd, transverse diameter of the right atrium; LAlr, left-right dimension of the left atrium; LAap, anteroposterior dimension of the left atrium; RVa, area of the right ventricle; LVa, area of the left ventricle; RAa, right atrial area; LAa, left atrial area.

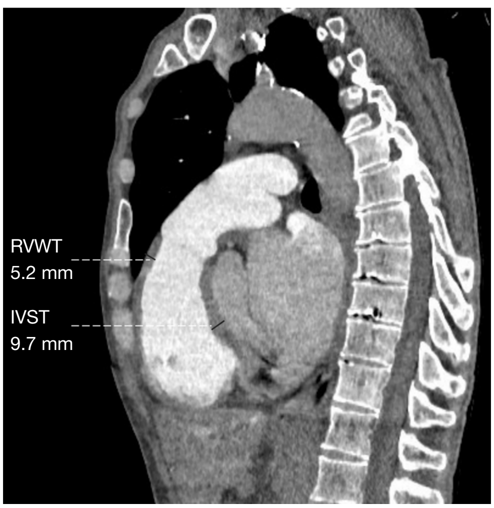

Figure 4 Measurement of the RVWT and IVST on the sagittal position obtained through the multiplanar reconstruction method. RVWT, right ventricular free wall thickness; IVST, interventricular septal thickness.

(percentage), and the chi-squared test was used for the comparison of different groups. Univariate and stepwise multivariate binary logistic regression analysis was used to evaluate the independent predictors for CTEPH, and receiver operator characteristic (ROC) curve analysis was performed for cardiovascular parameters and prediction models, with the area under the curve (AUC), sensitivity, and specificity being calculated. The correlations between CTPA cardiovascular metrics, hemodynamics, and N-terminal pro-B-type natriuretic peptide (NT-proBNP) were analyzed using Spearman rank correlation analysis. The classification of correlation coefficient (r) was as follows: $r \leq 0.3$ indicated no or a very weak correlation, $0.3 < r \leq 0.5$ indicated low correlation, $0.5 < r \leq 0.8$ indicated moderate correlation, and $r > 0.8$ indicated high correlation. Interobserver consistency was evaluated using intraclass correlation coefficient (ICC), with an ICC greater than 0.8 indicating high consistency. A 2-sided P value of less than 0.05 indicated statistical significance.

Results

Patient characteristics

This study included 180 patients (males n=86; age 55.5±12.0 years old) (*Figure 1*). *Table 1* indicates the demographics, hemodynamics, and clinical characteristics of our study cohort. Patients were placed into groups of mPAP ≤20 mmHg (n=50) and mPAP >20 mmHg (n=130) according to the 2022 ESC/ERS guidelines (1). Among the 50 patients without PH (mPAP =14.7±3.3 mmHg; PVR =1.3 WU), there were

Table 1 Demographic characteristics and hemodynamics of all included patients

Characteristics	Total patients (n=180)	mPAP ≤20 mmHg group (n=50)	mPAP >20 mmHg group (n=130)	mPAP ≥25 mmHg group (n=119)	P value[a]	P value[b]
Age (years)	55.5±12.0	53.2±12.7	56.4±11.6	56.3 ±11.2	0.101	0.916
Gender (male/female)	86/94	26/24	60/70	54/65	0.485	0.902
BMI (kg/m^2)	24.5±3.4	24.9±3.5	24.4±3.3	24.3±3.2	0.291	0.803
NT-proBNP (pg/mL)	203 [64–876]	51 [20–84]	469 [128–1,177]	518 [170–1,256]	<0.001**	0.634
6MWD (m)	410±116	498±89	387±112	377±111	<0.001**	0.529
WHO FC I/II/III/IV	48/64/53/15	34/9/6/1	14/55/47/14	10/50/45/14	<0.001**	0.927
Resting hemodynamics						
mPAP (mmHg)	32.0±14.2	14.7±3.3	38.6±10.8	40.3±10.1	<0.001**	0.275
sPAP (mmHg)	57.0±26.3	26.5±6.9	68.8±21.0	71.7±19.4	<0.001**	0.253
dPAP (mmHg)	18.6±9.0	7.8±3.2	22.8±6.7	23.5±6.5	<0.001**	0.345
mRAP (mmHg)	4 [2–6]	2 [0.8–4]	5 [2–7]	5 [2–7]	<0.001**	0.774
PAWP (mmHg)	9.4±2.9	9.2±3.0	9.5±2.8	9.4±2.8	0.504	0.665
sBP (mmHg)	131.3±19.8	133.2±20.3	130.5±19.6	130.5±19.8	0.434	0.985
dBP (mmHg)	82.9±13.5	81.3±12.7	83.6±13.8	83.9±13.9	0.323	0.878
PVR (Wood units)	6.3 [2.1–11.2]	1.3 [0.7–1.8]	8.8 [5.8–13.5]	9.6 [6.3–13.8]	<0.001**	0.408
CO (L/min)	3.7±1.3	4.6±1.3	3.4±1.1	3.3±1.1	<0.001**	0.721
Cardiac index (L/min/m^2)	2.2±0.7	2.6±0.7	2.0±0.6	1.95±0.6	<0.001**	0.751

Data are presented as mean ± standard deviation, median [interquartile range], or number (frequency). [a], statistical difference between the mPAP >20 mmHg group and the mPAP ≤20 mmHg group; [b], statistical difference between the mPAP >20 mmHg group and the mPAP ≥25 mmHg group. **, P<0.001 is considered statistically significant. mPAP, mean pulmonary arterial pressure; BMI, body mass index; NT-proBNP, N-terminal pro-brain natriuretic peptide; 6MWD, 6-minute walking distance; WHO FC, World Health Organization functional class; sPAP, systolic pulmonary arterial pressure; dPAP, diastolic pulmonary arterial pressure; mRAP, mean right atrial pressure; PAWP, pulmonary artery wedge pressure; sBP, systolic blood pressure; dBP, diastolic blood pressure; PVR, pulmonary vascular resistance; CO, cardiac output.

43 patients with chronic thromboembolic pulmonary disease (CTEPD), 4 patients with Takayasu arteritis, 2 patients with fibrosing mediastinitis, and 1 patient with Behcet syndrome. All 130 patients with PH (mPAP >20 mmHg) were diagnosed with CTEPH. *Table 1* shows that there were no significant differences in age, gender, or body mass index (BMI) between patients with and without PH (P>0.05). According to the 2015 ESC/ERS guidelines, there were 61 patients with mPAP <25 mmHg and 119 patients with mPAP ≥25 mmHg who were diagnosed as CTEPH. *Table 1* also indicates that the age, gender, and BMI between the patients with CTEPH and mPAP >20 mmHg and those with mPAP ≥25 mmHg were comparable (P>0.05).

Cardiovascular metrics on CTPA

Table 2 shows the interobserver ICC for cardiovascular metrics from CTPA in all patients, which ranged from 0.818 to 0.977 (P<0.01). Based on the new guidelines, patients with CTEPH had a higher Cobb angle, MPAd, RVtd, RVld, RAtd, RAld, RVa, RAa, RVWT, MPAd/AAd, RVtd/LVtd, RVa/LVa, and RVWT/IVST compared to the patients without PH, as shown in *Table 2* (P<0.05). However, *Table 3* demonstrates that these cardiovascular metrics including Cobb angle, MPAd, RVtd, RVld, RAtd, RAld, RVa, RAa, RVWT, MPAd/AAd, RVtd/LVtd, RVa/LVa, and RVWT/IVST were comparable between the 2022 and 2015 ESC/ERS criteria (P>0.05).

Table 2 The cardiovascular parameters of CTPA in patients with chronic thromboembolic pulmonary hypertension (mPAP >20 mmHg) and without pulmonary hypertension (mPAP ≤20 mmHg) according to the 2022 ESC/ERS guidelines

Variable	Interobserver agreement (ICC, N=180)	Group without PH, mPAP ≤20 mmHg (N=50)	CTEPH group, mPAP >20 mmHg (N=130)	P value
Cobb angle (degree)	0.970	36.7±8.1	54.2±13.4	<0.001**
MPAd (mm)	0.961	26.7±3.5	35.6±5.4	<0.001**
AAd (mm)	0.960	32.8±5.3	32.2±4.8	0.447
RVtd (mm)	0.963	35.8±4.0	47.7±9.7	<0.001**
RVld (mm)	0.974	67.2±10.4	75.0±9.5	<0.001**
RAtd (mm)	0.912	43.3±6.4	54.9±11.7	<0.001**
RAld (mm)	0.904	39.4±8.0	50.4±11.6	<0.001**
LVtd (mm)	0.974	39.4±6.9	36.0±8.0	0.009*
LVld (mm)	0.929	70.0±8.9	67.4±9.7	0.096
LAlr (mm)	0.870	55.2±8.4	56.3±9.2	0.462
LAap (mm)	0.874	39.2±7.3	39.0±7.0	0.90
RVa (mm^2)	0.957	18.7±5.3	29.0±9.3	<0.001**
RAa (mm^2)	0.947	15.0±4.7	24.4±10.5	<0.001**
LVa (mm^2)	0.961	24.2±6.5	21.6±6.8	0.029*
LAa (mm^2)	0.928	17.5±4.9	16.6±5.3	0.172
RVWT (mm)	0.818	3.1±1.1	5.5±1.6	<0.001**
IVST (mm)	0.942	9.9±2.1	9.2±2.1	0.056
MPAd/AAd ratio	0.971	0.83±0.15	1.13±0.24	<0.001**
RVtd/LVtd ratio	0.974	0.93±0.14	1.41±0.50	<0.001**
RVa/LVa ratio	0.977	0.79±0.16	1.5±0.80	<0.001**
RVWT/IVST ratio	0.866	0.32±0.11	0.63±0.22	<0.001**

Continuous variables are expressed as mean value ± standard deviation. *, P<0.05 and **, P<0.001 are considered statistically significant. CTPA, computed tomography pulmonary angiography; mPAP, mean pulmonary arterial pressure; ESC, European Society of Cardiology; ERS, European Respiratory Society; ICC, intraclass correlation coefficient; PH, pulmonary hypertension; CTEPH, chronic thromboembolic pulmonary hypertension; MPAd, diameter of the main pulmonary artery; AAd, diameter of the ascending aorta; RVtd, transverse diameter of the right ventricle; RVld, longitudinal diameter of the right ventricle; RAtd, transverse diameter of the right atrium; RAld, longitudinal diameter of the right atrium; LVtd, transverse diameter of the left ventricle; LVld, longitudinal diameter of the left ventricle; LAlr, left-right diameter of the left atrium; LAap, anteroposterior diameter of the left atrium; RVa, area of the right ventricle; RAa, area of the right atrium; LVa, area of the left ventricle; LAa, area of the left atrium; RVWT, right ventricular free wall thickness; IVST, interventricular septal thickness.

Univariate and forward multivariate binary logistic regression indicated that in both the old and new criteria, MPAd, RVtd, Cobb angle, and RVWT were independent predictors of CTPA for mPAP >20 mmHg (P<0.01) (*Table 4*). *Table 5* shows the ROC analysis of the cardiovascular metrics in the prediction of PH under the old and new criteria. Compared to the other metrics, the MPAd of 30.4 mm exhibited the highest AUC (0.934±0.021) in the diagnosis of mPAP >20 mmHg, with a sensitivity of 0.88 and a specificity of 0.90 (*Figure 5*).

Correlation of cardiovascular metrics and hemodynamics with clinical data

Table 6 shows that the Cobb angle (r=0.586 to 0.693), RVtd/LVtd (r=0.583 to 0.596), and RVa/LVa (r=0.629 to

Table 3 Cardiovascular metrics on CTPA in patients with chronic thromboembolic pulmonary hypertension according to the 2015 (mPAP ≥25 mmHg) and 2022 (mPAP >20 mmHg) ESC/ERS guidelines

Metric on CTPA	CTEPH group, mPAP >20 mmHg (N=130)	CTEPH group, mPAP ≥25 mmHg (N=119)	P value
Cobb angle (degree)	54.2±13.4	55.6±12.9	0.417
MPAd (mm)	35.6±5.4	36.1±5.2	0.542
AAd (mm)	32.2±4.8	32.1±4.7	0.916
RVtd (mm)	47.7±9.7	48.7±9.3	0.405
RVld (mm)	75.0±9.5	75.6±9.2	0.581
RAtd (mm)	54.9±11.7	55.7±11.6	0.575
RAld (mm)	50.4±11.6	51.0±11.8	0.665
LVtd (mm)	36.0±8.0	35.7±8.0	0.734
LVld (mm)	67.4±9.7	67.2±9.8	0.862
LAlr (mm)	56.3±9.2	56.6±9.1	0.789
LAap (mm)	39.0±7.0	38.7±6.8	0.765
RVa (mm^2)	29.0±9.3	30.0±9.0	0.411
RAa (mm^2)	24.4±10.5	25.1±10.7	0.614
LVa (mm^2)	21.6±6.8	21.4±6.8	0.762
LAa (mm^2)	16.6±5.3	16.5±5.2	0.945
RVWT (mm)	5.5±1.6	5.5±1.6	0.921
IVST (mm)	9.2±2.1	9.1±2.1	0.600
MPAd/AAd ratio	1.13±0.24	1.15±0.24	0.652
RVtd/LVtd ratio	1.41±0.50	1.45±0.50	0.439
RVa/LVa ratio	1.5±0.80	1.57±0.81	0.401
RVWT/IVST ratio	0.63±0.22	0.64±0.23	0.608

Continuous variables are expressed as mean value ± standard deviation. CTPA, computed tomography pulmonary angiography; mPAP, mean pulmonary arterial pressure; ESC, European Society of Cardiology; ERS, European Respiratory Society; CTEPH, chronic thromboembolic pulmonary hypertension; MPAd, diameter of the main pulmonary artery; AAd, diameter of the ascending aorta; RVtd, transverse diameter of the right ventricle; RVld, longitudinal diameter of the right ventricle; RAtd, transverse diameter of the right atrium; RAld, longitudinal diameter of the right atrium; LVtd, transverse diameter of the left ventricle; LVld, longitudinal diameter of the left ventricle; LAlr, left-right diameter of the left atrium; LAap, anteroposterior diameter of the left atrium; RVa, area of the right ventricle; RAa, area of the right atrium; LVa, area of the left ventricle; LAa, area of the left atrium; RVWT, right ventricular free wall thickness; IVST, interventricular septal thickness.

0.652) had a moderate correlation with mPAP, PVR, and NT-proBNP, respectively. Additionally, RVtd (r=0.368 to 0.570), RAtd (r=0.466 to 0.639), RAld (r=0.409 to 0.603), RVa (r=0.319 to 0.581), and RAa (r=0.432 to 0.629) also rspectively exhibited low to moderate correlations with mPAP, mRAP, PVR, and NT-proBNP. MPAd (r=0.482) and MPAd/AAd (r=0.391) had low correlations with mPAP and only weak correlations with PVR, NT-proBNP, and mRAP (r=0.143 to 0.262). There was a low negative correlation (r=−0.45) between CO and Cobb angle, while left ventricular metrics (LVld, LVtd, LVa) showed a low positive correlation (r=0.376 to 0.471) with CO.

Discussion

Due to the changes in the mPAP criteria for diagnosing PH, we comprehensively compared the cardiovascular metrics from CTPA in CTEPH between the 2022 ESC/ERS

Table 4 Binary stepwise logistic regression analysis for cardiovascular imaging predictors of pulmonary hypertension under the 2015 and 2022 diagnostic criteria

Variable	Nonstandardized coefficient		Walt value	P value	OR	95% CI	
	β	SE				Lower limit	Upper limit
mPAP >20 mmHg							
Cobb angle	0.102	0.044	5.478	0.019*	1.108	1.017	1.207
MPAd	0.240	0.095	6.354	0.012*	1.271	1.055	1.532
RVtd	0.162	0.063	6.575	0.01*	1.176	1.039	1.331
RVWT	1.296	0.397	10.664	0.001**	3.655	1.679	7.955
mPAP ≥25 mmHg							
Cobb angle	0.121	0.038	9.916	0.002**	1.129	1.047	1.217
MPAd	0.246	0.083	8.793	0.003**	1.279	1.087	1.505
RVtd	0.185	0.057	10.415	0.001**	1.203	1.075	1.345
RVWT	0.703	0.246	8.205	0.004**	2.020	1.249	3.269

*, P<0.05 and **, P<0.001 are considered statistically significant. OR, odds ratio; CI confidence interval; SE, standard error; mPAP, mean pulmonary arterial pressure; MPAd, diameter of the main pulmonary artery; RVtd, transverse diameter of the right ventricle; RVWT, the right ventricular free wall thickness.

guidelines (mPAP >20 mmHg) (1) and the 2015 ESC/ERS guidelines (mPAP ≥25 mmHg) (2). To our knowledge, this is the first study to analyze the difference in cardiovascular metrics on CTPA under the old and updated criteria. Our study produced several major findings: (I) there was no statistically significant difference in cardiovascular metrics for the diagnosis of PH between new and old guidelines; (II) MPAd, RVtd, Cobb angle, and RVWT on CTPA were independent predictors for mPAP >20 mmHg in patients with CTEPH; (III) compared to the other metrics, an MPAd of 30.4 mm exhibited the highest AUC, with a sensitivity of 0.88 and specificity of 0.90; (IV) cardiovascular metrics, especially metrics from the 4-chamber view of CTPA images moderately correlated with mPAP.

CTPA is a promising choice as the primary imaging method for suspected CTEPH due to its speed, wide availability, excellent spatial and temporal resolution, and ability to directly visualize chronic pulmonary embolism (16,17). Its high sensitivity and specificity for CTEPH allow for early diagnosis and help avoid advanced disease stages in patients with CTEPH (16). According to the 2022 ERS/ERS guidelines for the diagnosis of PH, cardiovascular metrics from CTPA, including Cobb angle, MPAd, RVtd, RVld, RAtd, RAld, RVa, RAa, RVWT, MPAd/AAd, RVtd/LVtd, RVa/LVa, and RVWT/IVST were significantly higher in patients with CTEPH than in patients without PH. These results are similar to those reported by Charters *et al.* (13) and Liu *et al.* (21), indicating that cardiovascular metrics on CTPA can predict mPAP >20 mmHg. Cardiovascular metrics from CTPA have been applied to assess PH (1,2,12,18). For instance, a cutoff value of 29 mm for MPAd has been used as an indicator of mPAP ≥25 mmHg. Corson *et al.* (22) reported an MPAd/AAd >1 as being an imaging marker of PH. Recently, a meta-analysis indicated that CT measurement MPAd/AAd ratio ≥1 has a combined sensitivity of 0.652 [95% confidence interval (CI): 0.579–0.719] and a combined specificity of 0.830 (95% CI: 0.796–0.880) in predicting mPAP ≥25 mmHg (12). In our study, according to the 2022 ERS/ERS guidelines, the sensitivity and specificity of a 30.4 mm cutoff value for MPAd in predicting mPAP >20 mmHg, respectively, was 0.88 and 0.90, whereas the sensitivity and specificity of a 0.98 cutoff value for MPAd/AAd in predicting mPAP >20 mmHg, respectively, was 0.76 and 0.84 in *Table 5*. Notably, both RVWT and RVWT/IVST ratio had a sensitivity of 0.90 and specificity of 0.80 in diagnosing mPAP >20 mmHg. Similarly, Swift *et al.* proposed that an MPAd of 30 mm represents a compromise threshold for identifying patients with mPAP >20 mmHg (5). In our study, *Table 5* shows the cutoff value of MPAd/AAd and other parameters indicating RV enlargement under the new guidelines were also similar to those of previous studies (12,23,24).

Table 5 The ROC curve of cardiovascular metrics on CTPA under the 2015 and 2022 ESC/ERS diagnostic criteria

Cardiovascular metric on CTPA	Cutoff value	AUC	95% CI		P value	Sensitivity	Specificity
			Lower limit	Upper limit			
CTPA metric for mPAP >20 mmHg							
Cobb angle (degree)	48.3	0.872±0.026	0.822	0.922	<0.001**	0.67	1.00
MPAd (mm)	30.4	0.934±0.021	0.892	0.976	<0.001**	0.88	0.90
RVtd (mm)	43.3	0.876±0.025	0.827	0.925	<0.001**	0.69	1.00
RAtd (mm)	49.7	0.819±0.033	0.755	0.883	<0.001**	0.69	0.86
RVa (mm^2)	24.5	0.842±0.031	0.781	0.904	<0.001**	0.72	0.86
RAa (mm^2)	15.4	0.808±0.034	0.742	0.875	<0.001**	0.83	0.66
RVWT (mm)	3.8	0.910±0.025	0.861	0.959	<0.001**	0.90	0.80
MPAd/AAd ratio	0.98	0.873±0.027	0.821	0.925	<0.001**	0.76	0.84
RVtd/LVtd ratio	0.99	0.860±0.028	0.806	0.914	<0.001**	0.84	0.80
RVa/LVa ratio	0.93	0.870±0.026	0.819	0.920	<0.001**	0.79	0.84
RVWT/IVST ratio	0.40	0.925±0.020	0.886	0.964	<0.001**	0.90	0.80
Prediction model	–	0.979±0.009	0.961	0.996	<0.001**	–	–
CTPA metric for mPAP ≥25 mmHg							
Cobb angle (degree)	46.2	0.892±0.023	0.847	0.937	<0.001**	0.77	0.87
MPAd (mm)	30.4	0.918±0.025	0.869	0.967	<0.001**	0.92	0.84
RVtd (mm)	43.3	0.900±0.023	0.854	0.946	<0.001**	0.73	0.97
RAtd (mm)	49.7	0.822±0.032	0.760	0.885	<0.001**	0.72	0.82
RVa (mm^2)	24.5	0.868±0.028	0.813	0.924	<0.001**	0.77	0.87
RAa (mm^2)	15.8	0.802±0.033	0.737	0.868	<0.001**	0.86	0.66
RVWT (mm)	3.8	0.843±0.032	0.780	0.906	<0.001**	0.89	0.66
MPAd/AAd ratio	0.98	0.856±0.030	0.798	0.915	<0.001**	0.78	0.77
RVtd/LVtd ratio	0.99	0.882±0.025	0.833	0.930	<0.001**	0.87	0.85
RVa/LVa ratio	0.92	0.898±0.022	0.854	0.942	<0.001**	0.85	0.80
RVWT/IVST ratio	0.45	0.891±0.024	0.844	0.938	<0.001**	0.85	0.77
Prediction model	–	0.964±0.014	0.936	0.992	<0.001**	–	–

Prediction model = Cobb angle + MPAd + RVtd + RVWT. Continuous variables are expressed as mean value ± standard deviation. **, P<0.001 is considered statistically significant. ROC, receiver operator characteristic curve; CTPA, computed tomography pulmonary angiography; ESC, European Society of Cardiology; ERS, European Respiratory Society; AUC, area under ROC curve; CI, confidence interval; mPAP, mean pulmonary arterial pressure; MPAd, diameter of the main pulmonary artery; RVtd, transverse diameter of the right ventricle; RAtd, transverse diameter of the right atrium; RVa, area of the right ventricle; RAa, area of the right atrium; RVWT, right ventricular free wall thickness; AAd, diameter of the ascending aorta; LVtd, transverse diameter of the left ventricle; LVa, area of the left ventricle; IVST, interventricular septal thickness.

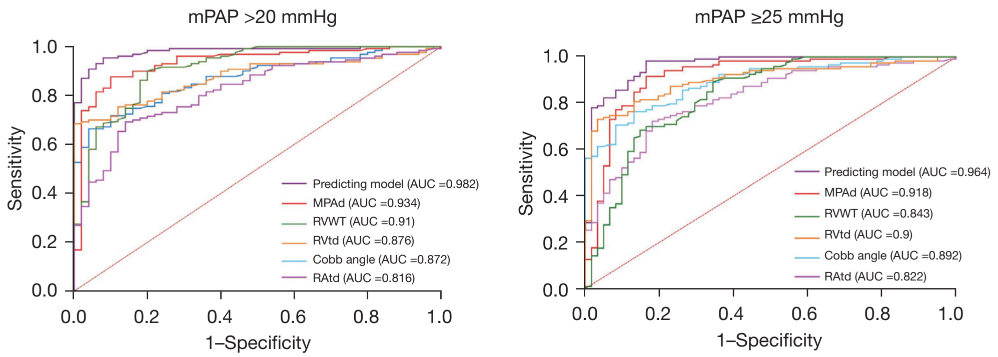

Figure 5 The ROC of cardiovascular metrics and prediction models for diagnosing chronic thromboembolic pulmonary hypertension under both the 2015 and 2022 ESC and the ERS guidelines. (A) ROC of cardiovascular metrics and prediction models for diagnosing CTEPH under the new 2022 criteria (mean pulmonary artery pressure >20 mmHg). (B) ROC of the cardiovascular metrics and prediction models for diagnosing CTEPH under the old 2015 criteria (mPAP ≥25 mmHg). ROC, receiver operating characteristic; ESC, European Society of Cardiology; ERS, European Respiratory Society; mPAP, mean pulmonary artery pressure; AUC, area under the curve; CTEPH, chronic thromboembolic pulmonary hypertension; MPAd, diameter of the main pulmonary artery; RVWT, right ventricular free wall thickness; RVtd, transverse dimension of right ventricle; RAtd, transverse dimension of right atrium.

In current study, there was no statistically significant differences in cardiovascular metrics between patients with mPAP >20 mmHg and mPAP ≥25 mmHg. The lack of differences in the cardiovascular parameters of CTPA between the old and new criteria for PH may be attributed to the following: (I) the difference of 4 mmHg in mPAP may have a limited impact on the morphological changes in the pulmonary artery and right heart; (II) the lower mPAP criterion may not fully capture the clinical condition or reflect the underlying pathological process itself (19); (III) the few cases with mPAP between 21 and 24 mmHg might have limited the significant differences in cardiovascular parameters between the old and new diagnostic criteria; (IV) the accuracy of cutoff values for cardiovascular parameters may be influenced by various factors, such as patient selection representing different subtypes of PH. Further investigations with larger cohorts are needed to confirm these findings.

In addition, our study demonstrated that Cobb angle, MPAd, RVtd, and RVWT on CTPA were independent predictors of PH for patients with suspected CETPH regardless of whether the new or old diagnostic criteria were used. Previous studies have focused on the impact of right ventricular changes on PH (14,25,26), while the right atrium in CTPA has been largely overlooked. Our study found that the RAtd in the 4-chamber view moderately correlated with mPAP. This indicates that RAtd may reflect mPAP and aid in PH evaluation (4). The Cobb angle also showed a moderate correlation with mPAP and PVR, and its cutoff value of 48.3° for predicting PH with mPAP >20 mmHg had high specificity and low sensitivity.

Limitations

There are some limitations in this study. First, we employed a single-center retrospective study design. As there were few cases of other subtypes of PH cases, they were excluded, with only patients with CTEPH being analyzed; this inevitably limits the generalizability of these findings to other types of PH. Therefore, future studies will include cases with precapillary and postcapillary PH. Second, only mPAP was used as the grouping criteria, and thus the alterations of cardiovascular metrics on CTPA under the different PVRs (2 and 3 WU) remain unknown. Third, RHC is not a routine procedure for healthy individuals, so only a small number of patients with normal and mild PH were included. Whether cardiovascular metrics in patients with mPAP ranging from 21 to 24 mmHg are different from those of patients with mPAP ≤20 mmHg is unclear, and the optimal cutoff values of cardiovascular metrics on CTPA in PH patients need to be further investigated.

Conclusions

Cardiovascular metrics on CTPA were similar between the updated and old PH guidelines. MPAd, Cobb angle,

Table 6 The correlation of cardiovascular metrics on CTPA with hemodynamics and serum NT-proBNP

Cardiovascular metric on CTPA	mPAP (mmHg)	mRAP (mmHg)	PVR (WU)	PAWP (mmHg)	CO (L/min)	NT-proBNP (pg/mL)
Cobb angle (degree)	0.586**	0.328**	0.613**	−0.114	−0.450**	0.693**
MPAd (mm)	0.482**	0.218*	0.262**	0.037	−0.042	0.230 **
AAd (mm)	−0.074	−0.005	−0.058	0.041	−0.080	−0.021
RVtd (mm)	0.518**	0.368**	0.428**	−0.067	−0.191*	0.570**
RVld (mm)	0.182**	0.174*	0.080	0.064	0.046	0.223**
RAtd (mm)	0.558**	0.466**	0.478**	0.011	−0.258**	0.639**
RAld (mm)	0.467**	0.409**	0.425**	0.030	−0.289**	0.603**
LVtd (mm)	−0.333**	−0.032	−0.43**	0.194*	0.376**	−0.307**
LVld (mm)	−0.312**	−0.068	−0.444**	0.088	0.471**	−0.346**
LAlr (mm)	0.151	0.186*	0.090	0.091	0.019	0.082
LAap (mm)	−0.079	0.111	−0.211*	0.115	0.257*	−0.146
RVa (mm^2)	0.487**	0.319**	0.410**	−0.068	−0.190*	0.581**
RAa (mm^2)	0.495**	0.432**	0.442**	−0.002	0.270**	0.629**
LVa (mm^2)	−0.335**	−0.035	−0.438**	0.138	0.430**	−0.294**
LAa (mm^2)	−0.023	−0.118	−0.164*	0.209*	0.248**	−0.115
RVWT (mm)	0.129	0.041	−0.013	0.148	0.119	−0.014
IVST (mm)	−0.177*	−0.081	−0.259**	0.159	0.218*	−0.257**
MPAd/AAd ratio	0.391**	0.143*	0.222*	0.035	0.042	0.200*
RVtd/LVtd ratio	0.583**	0.248*	0.593**	−0.174	−0.382**	0.596**
RVa/LVa ratio	0.629**	0.265**	0.642**	−0.146	−0.442**	0.652**
RVWT/IVST ratio	0.266**	0.121	0.197*	−0.024	−0.069	0.205*

*, P<0.05 and **, P<0.001 are considered statistically significant. CTPA, computed tomography pulmonary angiography; NT-proBNP, N-terminal pro-brain natriuretic peptide; mPAP, mean pulmonary arterial pressure; mRAP, mean right atrial pressure; PVR, pulmonary vascular resistance; WU, Wood units; PAWP, pulmonary artery wedge pressure; CO, cardiac output; MPAd, diameter of the main pulmonary artery; AAd, diameter of the ascending aorta; RVtd, transverse diameter of the right ventricle; RVld, longitudinal diameter of the right ventricle; RAtd, transverse diameter of the right atrium; RAld, longitudinal diameter of the right atrium; LVtd, transverse diameter of the vleft ventricle; LVld, longitudinal diameter of the left ventricle; LAlr, left-right diameter of the left atrium; LAap, anteroposterior diameter of the left atrium; RVa, area of the right ventricle; RAa, area of the right atrium; LVa, area of the left ventricle; LAa, area of the left atrium; RVWT, right ventricular free wall thickness; IVST, interventricular septal thickness.

RVtd, and RVWT on CTPA were independent predictors of mPAP >20 mmHg. An MPAd of 30.4 mm represents a compromise threshold for identifying mPAP >20 mmHg in patients with CTEPH.

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Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://qims.amegroups.com/article/view/10.21037/qims-23-250/rc

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://qims.amegroups.com/article/view/10.21037/qims-23-250/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013) and was approved by the institutional ethics board of China-Japan Friendship Hospital (No. 2022-KY-048). Individual consent for this retrospective analysis was waived.

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