

Quantitative assessment of risk stratification of acute pulmonary embolism based on three-dimensional computed tomography bronchography and angiography

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Background: Accurate assessment and severity grading of acute pulmonary embolism (APE) currently relies on the Simplified Pulmonary Embolism Severity Index (sPESI) combined with biomarkers or right ventricular function indicators in clinical practice, which increases implementation complexity. Computed tomography pulmonary angiography (CTPA) remains the preferred imaging modality for confirming APE, while the commonly used Qanadli semi-quantitative scoring system has limited accuracy. This study aimed to explore the feasibility of quantitatively assessing risk stratification in patients with APE using three-dimensional computed tomography bronchography and angiography (3D-CTBA).

Methods: Sixty-one patients with APE who underwent CTPA at the First Affiliated Hospital of Hebei North University were retrospectively enrolled. Clinical data were collected, and 3D-CTBA was performed using Mimics software to reconstruct pulmonary artery and embolism models. The thrombus volume-to-pulmonary artery volume ratio was calculated. Spearman correlation analysis was used to evaluate associations between this ratio, the computed tomography pulmonary artery obstruction index (Qanadli score), and related parameters, including the right ventricle-to-left ventricle (RV/LV) ratio and laboratory biomarkers. Receiver operating characteristic (ROC) curves were constructed, and the area under the curve (AUC) was calculated to assess the predictive efficacy of the thrombus volume-to-pulmonary artery volume ratio for risk stratification.

Results: A strong correlation was observed between the thrombus volume-to-pulmonary artery volume ratio and the Qanadli score ($r=0.732$, $P<0.001$). The ratio showed moderate correlations with RV/LV ($r=0.448$, $P<0.001$), B-type natriuretic peptide (BNP; $r=0.566$, $P<0.001$), and creatinine kinase-myocardial band (CK-MB; $r=0.495$, $P<0.001$), and a weak correlation with D-dimer ($r=0.371$, $P=0.003$). In contrast, the Qanadli score correlated weakly with RV/LV ($r=0.381$, $P=0.002$) and moderately with BNP ($r=0.439$, $P<0.001$) and CK-MB ($r=0.467$, $P<0.001$), but showed no correlation with D-dimer ($r=0.136$, $P=0.30$). In ROC curve analysis, the AUC for the thrombus volume-to-pulmonary artery volume ratio was 0.847, compared with 0.811 for the Qanadli score ($Z=0.629$, $P=0.53$).

Conclusions: The thrombus volume-to-pulmonary artery volume ratio derived from 3D-CTBA provides a reliable quantitative method for risk stratification in patients with APE. This approach may serve as a complementary or alternative tool to the Qanadli score in clinical practice.

Keywords: Acute pulmonary embolism (APE); risk stratification; computed tomography pulmonary artery obstruction index (Qanadli score); thrombus volume-to-pulmonary artery volume ratio; clot burden

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Introduction

Acute pulmonary embolism (APE) is the third leading cause of cardiovascular death after myocardial infarction and stroke, accounting for approximately 100,000 deaths annually in the United States (1). The determination of APE severity is essential for effective clinical management, particularly in the emergency setting. Patients with APE should undergo thorough risk stratification to determine whether they may benefit from advanced therapeutic interventions (2). Current clinical approaches include the Pulmonary Embolism Severity Index (PESI) and the Simplified PESI (sPESI), often used in combination with

specific biomarker assessment (3). The European Society of Cardiology has established diagnostic criteria for APE involving right ventricular dysfunction, which include the right ventricular to left ventricular (RV/LV) diameter ratio and serum levels of B-type natriuretic peptide (BNP) and troponin. This diagnostic strategy, when applied alongside the sPESI, provides a comprehensive framework for risk stratification in patients with APE (4). However, the combined application of multiple indicators/parameters also increases the difficulty of clinical implementation.

Computed tomography pulmonary angiography (CTPA) has become the primary imaging modality for patients with suspected APE (5,6), providing a reliable means for establishing a definitive diagnosis (7-9). In recent years, a growing body of research has highlighted the potential of pulmonary artery obstruction index (PAOI) for assessing embolism severity in patients with APE (10,11). This index quantifies thrombus load and has emerged as a promising tool in clinical practice. The most widely used PAOI is the Qanadli score, a semi-quantitative method for estimating thrombus burden, although its accuracy in reflecting the true degree of vascular obstruction remains limited. In this study, three-dimensional computed tomography bronchography and angiography (3D-CTBA) was applied to measure pulmonary artery and thrombus volumes. By calculating the ratio of thrombus volume to pulmonary artery volume, thrombus load was evaluated using a quantitative rather than semi-quantitative approach, thereby ensuring greater accuracy in its assessment. We present this article in accordance with the TRIPOD reporting checklist (available at <https://jtd.amegroups.com/article/view/10.21037/jtd-2025-1574/rc>).

Methods

Study subjects

Between December 2020 and December 2022, general clinical data and relevant laboratory test results were retrospectively collected from patients diagnosed with APE using the medical record system of the First Affiliated Hospital of Hebei North University. Patients were included if they had a definitive diagnosis of APE established by CTPA. The diagnosis required CTPA images showing,

Highlight box

Key findings

- This study introduces a novel, three-dimensional computed tomography-based method for calculating the thrombus-to-pulmonary artery volume ratio in a quantitative manner. This provides an objective measure of clot burden in acute pulmonary embolism (APE).

What is known and what is new?

- The right ventricle-to-left ventricle (RV/LV) ratio, B-type natriuretic peptide (BNP), and troponin levels, when combined with simplified Pulmonary Embolism Severity Index, provide comprehensive risk stratification for patients with APE. Computed tomography pulmonary angiography offers reliable evidence for definitive diagnosis. The most widely used pulmonary artery obstruction index currently is the Qanadli score, a semi-quantitative method for estimating thrombus burden. However, its accuracy in reflecting the true degree of vascular obstruction remains limited.
- It demonstrates a strong correlation between the quantitative thrombus ratio and the established Qanadli score, as well as significant associations with the RV/LV ratio BNP and creatinine kinase-myocardial band. Receiver operating characteristic analysis reveals that the thrombus volume ratio [area under the curve (AUC) =0.847] performs comparably to—or better than—the Qanadli score (AUC =0.811) in stratifying APE risk.

What is the implication, and what should change now?

- It highlights the clinical utility of three-dimensional computed tomography bronchography and angiography as a complementary tool for risk prediction. It offers a more accurate and individualised assessment of embolism severity, which could support improved clinical decision-making and personalised treatment planning.

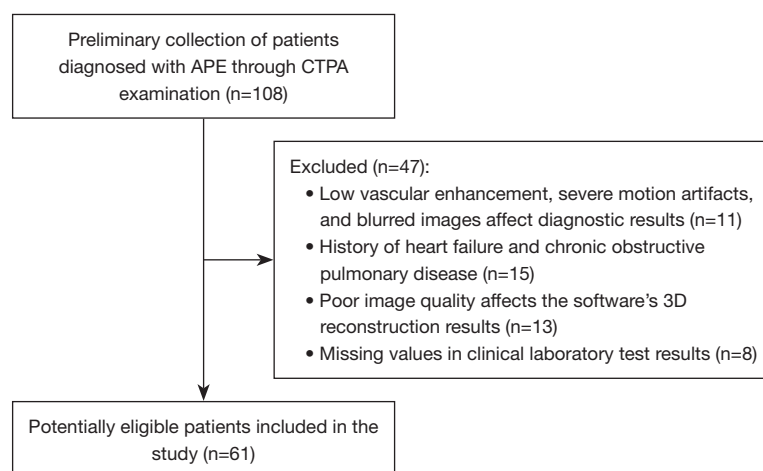


Figure 1 Patient inclusion and exclusion flowchart. 3D, three-dimensional; APE, acute pulmonary embolism; CTPA, computed tomography pulmonary angiography.

in at least two consecutive levels of the pulmonary artery lumen, a low-density filling defect, luminal stenosis, or occlusion (12). Patients were excluded if they had a previous history of APE. They were also excluded if the CTPA images contained artifacts or other factors that interfered with diagnosis and image reconstruction, or if their clinical data were incomplete (*Figure 1*). The study was conducted in accordance with the Declaration of Helsinki and its subsequent amendments. The study was approved by the Ethics Committee of the First Affiliated Hospital of Hebei North University (No. k2025166) and individual consent for this retrospective analysis was waived.

Patients were classified into low-risk and intermediate-risk groups according to the 2019 European Society of Cardiology guidelines. Patients with an sPESI score of 0 and negative markers of right ventricular dysfunction or myocardial injury were considered low-risk. Patients with an sPESI score >0, positive markers of right ventricular dysfunction or myocardial injury, or at risk of hypotension or shock were classified as intermediate-risk. Patients who presented with hypotension or shock were classified as high-risk, although this study primarily focused on differentiating between low- and intermediate-risk patients for the in-depth analysis.

CTPA scanning parameters

CTPA was performed using an Aquilion One Vision 320-row computed tomography (CT) scanner (Canon, Tokyo, Japan). The scanning parameters were as follows:

tube voltage of 120 kV and tube current regulated by SureExposure 3D automatic modulation technology. Automatic triggering was achieved with SureStart software, using a threshold of 200 HU. The scanning direction was from head to foot. An isotonic contrast agent (320 mgI/mL) was administered through the right median cubital vein at a rate of 4.0 mL/s, with a dosage of 1.0 mL/kg, followed by a 40-mL saline flush at the same rate.

Image processing and analysis

3D reconstruction of the bronchovascular bundle

CTPA images in DICOM format were sequentially imported into Mimics software and processed using the Thresholding tool. A blinded approach was applied during image processing: operators did not have access to patient names, risk stratification, or other predictive factors when obtaining measurement parameters. This ensured that the objectivity of the assessment was not influenced by prior knowledge of clinical variables. The CT threshold was adjusted as needed to clearly display the pulmonary artery. The pulmonary artery region was initially segmented using regional growth and dynamic regional growth algorithms. The editing function was then used to manually delineate the embolic region, and 3D models of the pulmonary artery and embolus were reconstructed separately. These models were subsequently merged using the combine function to create a single integrated structure. The software enabled distinct color coding of the pulmonary artery, bronchus, and embolus, allowing each structure to be clearly differentiated.

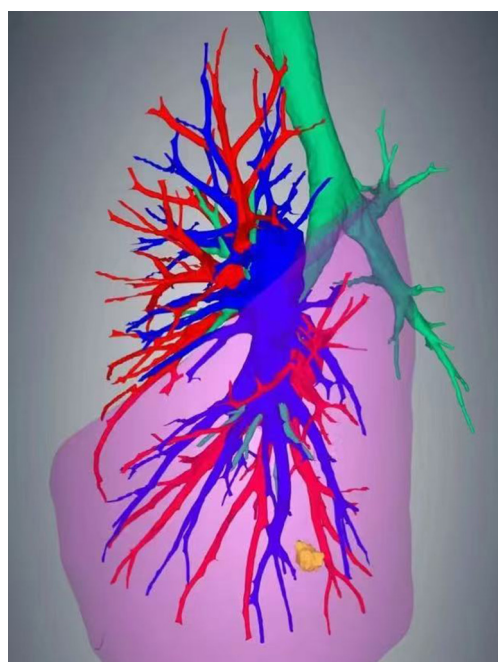


Figure 2 3D-CTBA-generated image showing the bronchus (green), right pulmonary vein (blue), right pulmonary artery (red), right lower lobe (pink), and right lower lobe basal segment thrombus (yellow). 3D-CTBA, three-dimensional computed tomography bronchography and angiography.

The reconstructed images could be displayed, hidden, or adjusted for transparency, and they could be rotated to facilitate observation from multiple angles (*Figure 2*). Image analysis was performed using both objective measurements and subjective scoring methods.

Thrombosis load calculation

Thrombus and pulmonary artery volumes were derived from 3D-CTBA. Thrombus volume was defined as the sum of all individual embolus volumes. Quantitative thrombus load was then calculated as the ratio of thrombus volume to pulmonary artery volume (*Figure 3*), representing the degree of luminal obstruction within the pulmonary arteries caused by emboli.

Qanadli score calculation

The Qanadli score was calculated using the following formula: $[\Sigma (n \times d) / 40] \times 100\%$. In this formula, n represents the number of embolized segmental arteries. If an embolus was present in a pulmonary segmental artery, it was recorded as 1. The score for an artery was the sum of all its distal pulmonary segments. An isolated subsegmental

artery embolus was considered a partial obstruction of the corresponding pulmonary segmental artery and was also recorded as 1 point. The variable d represents the degree of obstruction: 2 for complete embolization, 1 for partial embolization, and 0 for no embolization. The maximum possible score is 40 (9).

RV/LV calculation

Following previously described methods (13), measurements were performed at the four-chamber view level on conventional CTPA axial images. The longest diameter of the RV short axis was measured as the distance from the free wall of the RV to the inner wall of the interventricular septum at the widest point at the level of the tricuspid valve. The longest diameter of the LV short axis was measured as the distance between the inner wall of the LV and the inner wall of the interventricular septum at the widest point at the level of the mitral valve (*Figure 4*).

Two attending physicians, each with more than five years of experience, independently measured embolus volume as well as RV and LV diameters, blinded to clinical data and study objectives. In cases of disagreement, the final measurement was determined by a senior expert with more than 10 years of experience in cardiovascular imaging diagnosis.

Data processing

This study included a total of 61 patients, all of whom had complete routine clinical data, laboratory test results, and software-derived measurements without missing values. Consequently, all analyses were performed using the complete dataset from the enrolled patients, without the need for imputation or other methods of handling missing data.

Statistical analysis

Data were analyzed using SPSS version 29.0 (IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test was applied to assess the normality of measurement data. Normally distributed variables were expressed as mean $\pm$ standard deviation, whereas non-normally distributed variables were expressed as median (interquartile range). Spearman correlation analysis was performed to evaluate the relationship between the thrombus volume-to-pulmonary artery volume ratio and the Qanadli score, as well as their correlations with the RV/LV ratio and laboratory serum markers. Receiver operating characteristic (ROC) curves were constructed, and the area under the curve (AUC) was calculated. A P value <0.05 was considered statistically

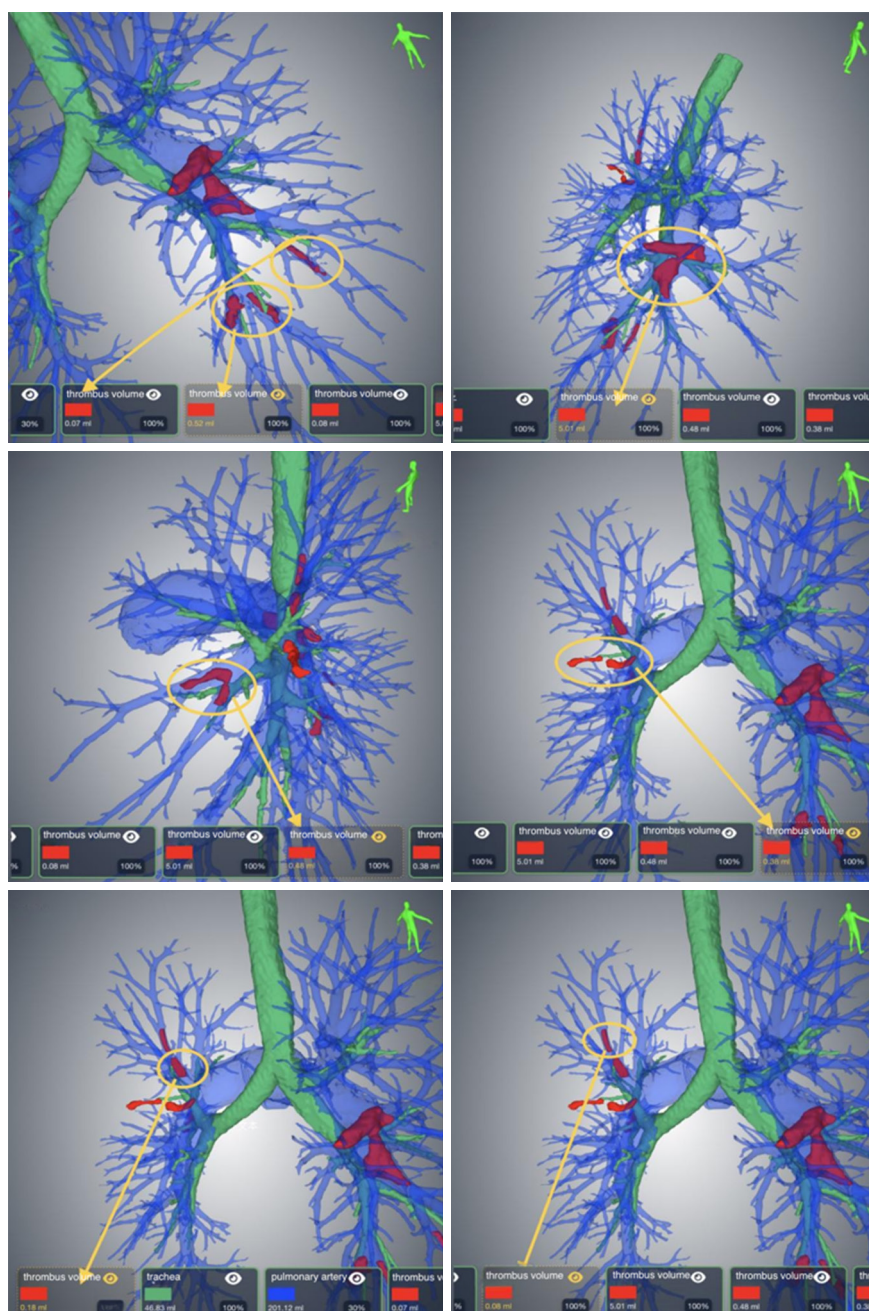


Figure 3 Quantitative assessment of thrombus load based on three-dimensional computed tomography bronchography and angiography. The reconstructed image shows the pulmonary artery (blue), trachea (green), and thrombus embolus (red).

significant.

Results

General information

A total of 61 patients with APE were included, comprising

31 men (50.82%) and 30 women (49.18%). The age range of the patients was 24–82 years, with a median age of 63 years and an interquartile range of 17 years. Among them, 11 patients were classified into the low-risk group and 50 patients into the intermediate- and high-risk groups. Age, sex, blood pressure, and pulse did not differ

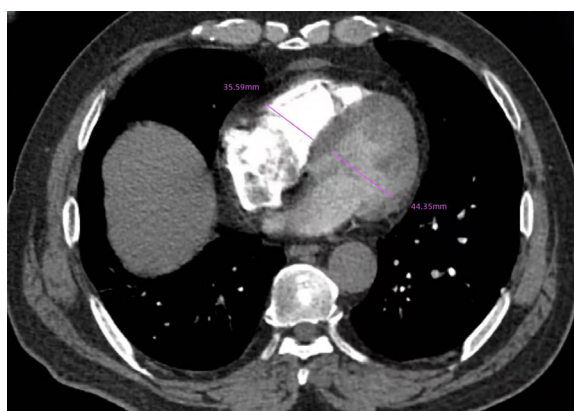


Figure 4 Measurement of right and left ventricular diameters in the four-chamber view of the heart.

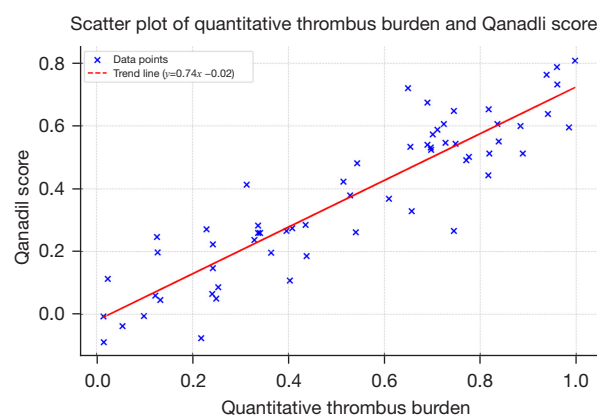


Figure 5 Scatter plot showing the correlation between quantitative thrombus burden and Qanadli score.

Table 1 Differences in age, sex, blood pressure, and pulse rate

Variable	Low-risk group (n=11)	Intermediate- and high-risk group (n=50)	U value	Z value	P value
Age (years)	63.0 (58.0–72.0)	62.0 (50.0–70.0)	226.500	−0.822	0.41
Pulse rate (times per minute)	88.0 (79.0–93.0)	82.0 (72.0–91.0)	212.000	−1.100	0.27
Blood pressure (mmHg)	16.0 (7.0–32.0)	31.0 (16.0–45.5)	177.000	−1.767	0.08
Sex	1.0 (1.0–1.0)	2.0 (1.0–2.0)	159.000	−2.439	0.07

Data are presented as median (interquartile range).

significantly between the low-risk and intermediate-/high-risk groups (Table 1).

Quantitative relationship between thrombus burden and Qanadli score

A significant positive correlation was observed between quantitative thrombus load, expressed as the thrombus volume-to-pulmonary artery volume ratio, and the Qanadli score ($r=0.732$, $P<0.001$; Figure 5).

Correlation of quantitative thrombus burden and Qanadli score with RV/LV, D-dimer, BNP, and creatinine kinase-myocardial band (CK-MB)

Quantitative thrombus burden demonstrated a moderate correlation with RV/LV ($r=0.448$, $P<0.001$), BNP ($r=0.566$, $P<0.001$), and CK-MB ($r=0.495$, $P<0.001$), and a weak correlation with D-dimer ($r=0.371$, $P=0.003$).

The Qanadli score correlated with RV/LV ($r=0.381$, $P=0.002$), BNP ($r=0.439$, $P<0.001$), and CK-MB ($r=0.467$,

$P<0.001$). No significant correlation was found between the Qanadli score and D-dimer ($P>0.05$; Table 2, Figure 6).

ROC curve analysis for assessing the predictive efficacy of thrombus volume-to-pulmonary artery volume ratio in APE risk stratification

ROC curve analysis of the thrombus volume-to-pulmonary artery volume ratio yielded an AUC of 0.847 [95% confidence interval (CI): 0.729–0.966] for discriminating low-risk APE. This demonstrated high accuracy (73.8%), with a sensitivity of 70.0% and a specificity of 90.9%. ROC curve analysis of the Qanadli score produced an AUC of 0.811 (95% CI: 0.691–0.931) for the low-risk APE group. The difference between the two AUCs was not statistically significant ($Z=0.629$, $P=0.53$; Table 3, Figure 7).

Quantitative evaluation process of APE risk stratification based on 3D-CTBA

Patient imaging data were first processed using Mimics

Table 2 Correlation of quantitative thrombus burden with RV/LV ratio, D-dimer, BNP, and CK-MB

Clinical parameters	Correlation coefficient	P value
Quantitative thrombus burden		
RV/LV	0.448 [†]	<0.001
D-dimer	0.371 [†]	0.003
BNP	0.566 [†]	<0.001
CK-MB	0.495 [†]	<0.001
Qanadli score		
RV/LV	0.381 [†]	0.002
D-dimer	0.136	0.30
BNP	0.439 [†]	<0.001
CK-MB	0.467 [†]	<0.001

[†], positive correlation. BNP, B-type natriuretic peptide; CK-MB, creatinine kinase-myocardial band; LV, left ventricle; RV, right ventricle.

software, which involved segmenting the pulmonary artery, delineating the embolic region, and reconstructing and merging the 3D models of both. The software allowed multimodal display and multi-angle visualization. Subsequently, analysis combined objective indicators with subjective scores. This included calculating the thrombus volume-to-pulmonary artery volume ratio and examining its correlation with the obstruction index, ventricular volume ratio, and biomarkers using Spearman correlation analysis. Finally, the measurement parameters obtained from this process, together with the collected clinical indicators, were applied to assess patient risk, enabling predictive risk stratification in APE.

Discussion

The results of this study demonstrate that 3D-CTBA can evaluate endovascular embolism in an intuitive and accurate manner. Moreover, the thrombus volume-to-pulmonary artery volume ratio derived from 3D-CTBA may serve as a supplement or alternative to the Qanadli score for risk stratification in patients with APE, thereby improving the prediction of disease severity.

The most common method of assessing thrombus burden is CTPA. Based on the location of the embolus in the pulmonary artery and a corresponding formula, the degree of luminal obstruction can be calculated. The Qanadli score is the most widely used method for thrombus

burden assessment on CTPA; however, it relies on visual estimation of vessel diameter and obstruction, making it subjective, prone to uncertainty, and potentially unable to fully reflect the clinical condition of the patient. Huang *et al.* (14) evaluated the association between thrombus volume, Qanadli score, biomarkers, and clinical outcomes using CT. Their results showed a significant correlation between the Qanadli score and thrombus volume ($r=0.69$, $P<0.001$). However, the Qanadli score was not correlated with RV dysfunction and did not play a major role in predicting short-term adverse outcomes in APE. The authors suggested that the Qanadli score has important limitations: each subsegmental embolus is assigned only one point regardless of its length or the number of affected subsegmental arteries; as a semi-quantitative method, it is also subject to high interobserver variability. Consequently, it may not accurately reflect the true thrombus burden. Furlan *et al.* (15) investigated the relationship between thrombus burden, as calculated by the Qanadli score, and short-term mortality in patients with APE. They found no significant correlation, which may be attributable to the lack of integration of disease severity and cardiopulmonary status in the scoring system. The Qanadli score primarily emphasizes the anatomical characteristics of thrombi while neglecting other important clinical and patient-specific factors, limiting its ability to accurately stratify individual risk. In contrast, the thrombus volume-to-pulmonary artery volume ratio derived from 3D-CTBA provides a quantitative assessment of thrombus burden while accounting for individual variability. This approach may more accurately reflect the true degree of luminal obstruction. The present study demonstrated a significant positive correlation between the thrombus volume-to-pulmonary artery volume ratio and the Qanadli score as assessed by 3D-CTBA, supporting the feasibility of this method for quantitative evaluation of thrombus burden in patients with APE.

The results of this study revealed a positive correlation between the thrombus volume-to-pulmonary artery volume ratio and key physiological markers, including the RV/LV diameter ratio and serum markers such as D-dimer, BNP, and CK-MB. The RV/LV ratio reflects right heart function, whereas serum markers such as D-dimer, BNP, and CK-MB indicate coagulation activity and cardiac injury. Their positive correlations with quantitative thrombus burden highlight that this parameter not only quantifies thrombus load but also reflects the impact of APE on cardiac function and overall physiological status (16,17). These findings

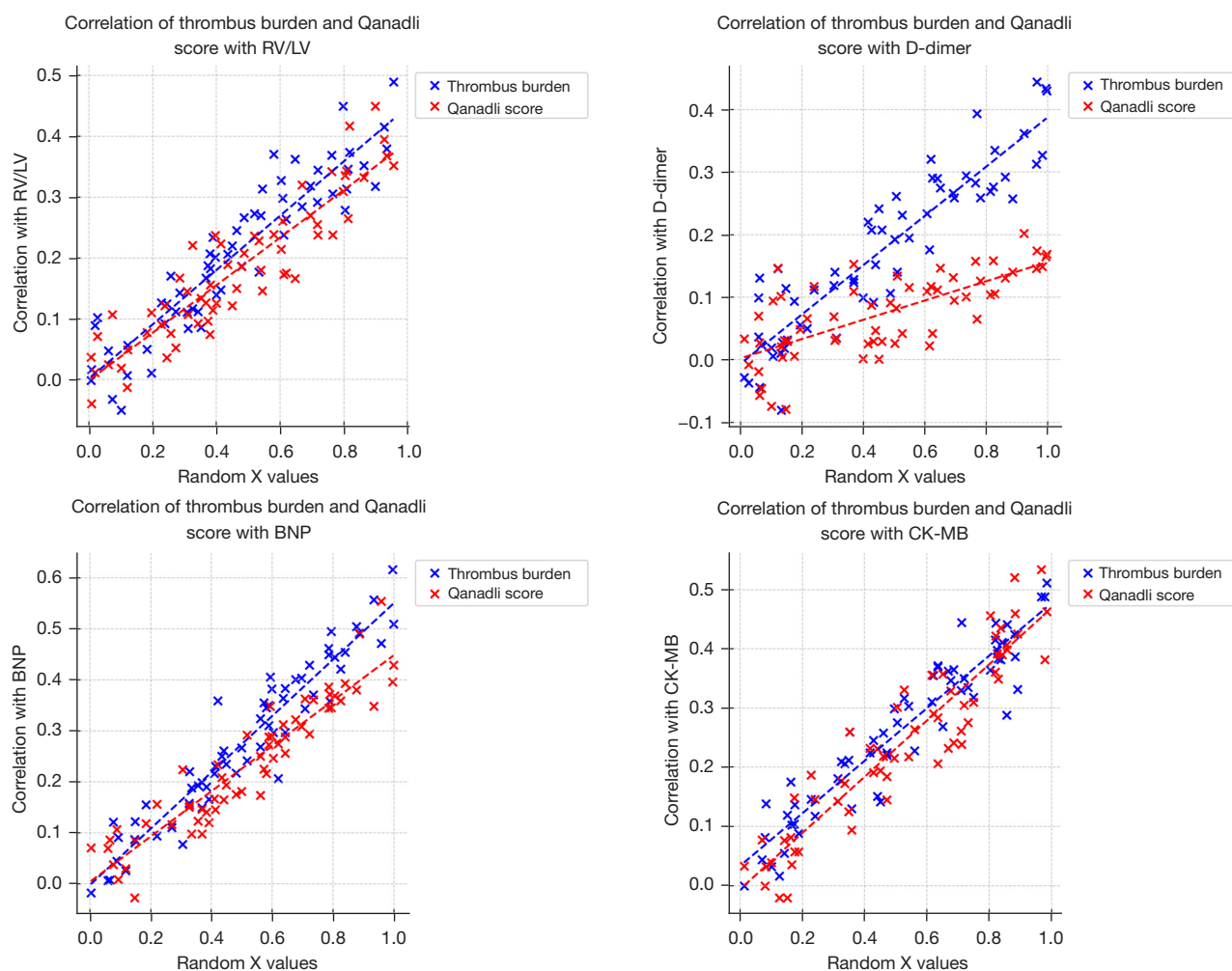


Figure 6 Scatter plots showing correlations of quantitative thrombus burden with RV/LV ratio, D-dimer, BNP, and CK-MB. BNP, B-type natriuretic peptide; CK-MB, creatinine kinase-myocardial band; LV, left ventricle; RV, right ventricle.

Table 3 ROC curve analysis of quantitative thrombus burden and Qanadli score

Scoring method	AUC (95% CI)	Accuracy (%)	Sensitivity (%)	Specificity (%)	Cutoff value	P value
Quantitative thrombus burden	0.847 (0.729–0.966)	73.80	70.00	90.90	0.841	<0.001
Qanadli score	0.811 (0.691–0.931)	65.60	58.00	100.0	0.886	<0.05

AUC, area under the curve; CI, confidence interval; ROC, receiver operating characteristic.

are consistent with previous reports. Jeebun *et al.* (18) demonstrated a correlation between thrombus load and D-dimer, BNP, troponin, and CK-MB in patients with APE. Haba *et al.* (19) reported that copeptin and the CT pulmonary embolism index (Mastora score) correlated significantly with clinical, biological, and imaging parameters

already validated as predictors of APE severity, including BNP, troponin, RV/LV ratio, and the PESI score, as well as with adverse cardiac events and mortality. Together, these findings suggest that the thrombus volume-to-pulmonary artery volume ratio derived from 3D-CTBA can assess APE severity in an intuitive and quantitative manner, offering a

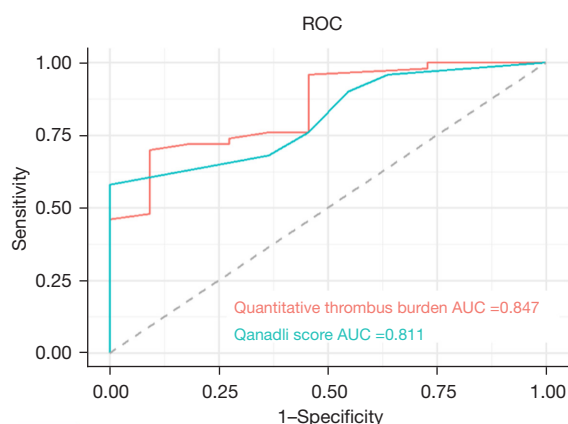


Figure 7 ROC curves for quantification of thrombus burden and Qanadli score. AUC, area under the curve; ROC, receiver operating characteristic.

reliable tool for clinical risk evaluation (5,20,21).

The results of this study showed that, in the ROC curve analysis of risk stratification in patients with APE, the AUC reached 0.847 (95% CI: 0.729–0.966). This finding highlights the clinical value of the quantitative thrombus load index derived from 3D-CTBA, which may provide complementary, fully quantitative information in comparison to the traditional Qanadli score. Thrombi of different composition, size, and location pose varying degrees of threat to patient survival (22–24). Previous studies assessing thrombus burden using thrombus volume demonstrated a strong positive correlation with the Qanadli score ($r^2=0.696$, $P<0.001$) and a moderate correlation with RV/LV ($r^2=0.392$, $P<0.001$). Both thrombus volume and RV/LV were identified as independent risk factors for high-risk APE and are considered important indicators for patient risk stratification. The thrombus volume-to-pulmonary artery volume ratio obtained by 3D-CTBA not only quantifies thrombus burden but also accounts for individual variability, thereby more accurately reflecting the true degree of pulmonary artery obstruction. This novel quantitative approach enables clinicians to more precisely assess patient risk, ensuring that high-risk patients receive timely and appropriate treatment (25–28). Furthermore, it offers potential utility for monitoring disease progression and treatment response in APE, allowing treatment regimens to be adjusted promptly as needed (29).

In addition, this study demonstrated that when the thrombus volume-to-pulmonary artery volume ratio was less than 0.02, cardiac biomarker levels remained low, indicating

a reduced risk of myocardial injury. When the ratio ranged from 0.02 to 0.04, cardiac biomarker levels began to rise, suggesting moderate cardiac strain or risk of injury. When the ratio exceeded 0.04, particularly when approaching or surpassing 0.08, serum levels of BNP, D-dimer, and CK-MB increased significantly, and the RV/LV ratio was also elevated. These findings indicate a high risk of myocardial injury or heart failure. The integration of these parameters provides clinicians with a more comprehensive assessment, enabling more accurate evaluation of APE severity and supporting timely diagnosis and appropriate treatment decisions.

There are several limitations in this study. The application of 3D-CTBA faces challenges related to operational complexity, technical requirements, and cost. 3D-CTBA analysis requires specialized software and additional processing time. With the rapid advancement of artificial intelligence technology, automated and rapid vascular segmentation and thrombus identification analysis are expected to be achieved in the future, thereby significantly enhancing the operational efficiency and clinical applicability of this method. We anticipate that by integrating with AI-assisted diagnostic systems, this quantitative tool will be incorporated into routine CTPA post-processing workflows. It will provide more objective and precise radiographic evidence for risk stratification and treatment decisions in APE without significantly increasing labor or time costs. Second, this study is a single-center retrospective investigation with a relatively small sample size (61 cases) and limited diversity. All enrolled patients were from a single hospital, potentially failing to adequately represent patient populations across different geographic regions, underlying conditions, and disease severity levels. Consequently, the generalizability of the findings is somewhat constrained. Therefore, future prospective studies involving multiple centers and large sample sizes are needed to further validate the effectiveness of the thrombus volume ratio based on 3D-CTBA in APE risk stratification and to assess the stability and applicability of this method. This will help overcome the limitations of single-center studies and further enhance the reliability and clinical applicability of the research findings.

Conclusions

In conclusion, the thrombus volume-to-pulmonary artery volume ratio derived from 3D-CTBA enables quantitative assessment of thrombus burden in patients with APE. This approach offers a novel tool for more accurate clinical risk

stratification and supports personalized treatment in clinical practice.

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Footnote

Reporting Checklist: The authors have completed the TRIPOD reporting checklist. Available at <https://jtd.amegroups.com/article/view/10.21037/jtd-2025-1574/rc>

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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 and its subsequent amendments. The study was approved by the Ethics Committee of the First Affiliated Hospital of Hebei North University (No. k2025166) and individual consent for this retrospective analysis was waived.

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