



Dual-energy computed tomography pulmonary angiography for pulmonary embolism: a three-tier evidence framework to guide individualized low-iodine scanning

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ABSTRACT

Dual-energy computed tomography (DECT) pulmonary angiography (CTPA) is widely studied for pulmonary embolism (PE) evaluation, but heterogeneity in protocols, platforms, and study designs complicates its clinical positioning. This narrative review, with structured search elements adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020, synthesized evidence from PubMed, Embase, Web of Science, and China National Knowledge Infrastructure (January 2016–June 2026); 28 studies were eligible (26 of 1,287 screened records and 2 identified through citation tracing). Evidence was organized into a three-tier framework (image quality, diagnostic performance, and clinical outcomes). Low-keV virtual monoenergetic imaging at 40–50 keV improves vascular attenuation and enables iodine load reduction to approximately 6 g in selected protocols. Pooled meta-analytic evidence shows no consistent diagnostic advantage of DECT over single-energy CT. The right ventricular/left ventricular diameter ratio remains the most stable prognostic indicator; DECT perfusion metrics have not surpassed it for mortality prediction. Iodine-map hypoperfusion in distal arteries is suspicious for, but not morphologically confirmed as, subsegmental PE; such findings carry a risk of overdiagnosis and warrant caution before anticoagulation. A body mass index- and estimated glomerular filtration rate-stratified protocol table with Oxford Centre for Evidence-Based Medicine 2011 evidence-level annotations is provided, and knowledge gaps in photon-counting CT, artificial intelligence, and cross-platform standardization are identified.

KEYWORDS

Dual-energy computed tomography, virtual monoenergetic imaging, pulmonary embolism, iodine contrast agent, subsegmental embolism, computed tomography pulmonary angiography quality control

1. Introduction

Pulmonary embolism (PE) is the third most common acute cardiovascular syndrome worldwide, with an annual incidence of 39–115 per 100,000.¹ Computed tomography (CT) pulmonary angiography (CTPA) is the first-line modality for suspected PE, with a high negative predictive value in patients with low or intermediate probability, consistent with the 2019 European Society of Cardiology/European Respiratory Society (ESC/ERS) and 2026 American Heart Association/American College of Cardiology (AHA/ACC) recommendations.^{1,2} Dual-energy CT (DECT) has expanded PE imaging: Low-keV virtual monoenergetic imaging (VMI) enhances vascular attenuation, whereas iodine maps enable simultaneous perfusion assessment. Yet a decade of clinical deployment has produced a paradox: a technology that doubles imaging information has not doubled diagnostic value.³ Nevertheless, the evidence base, spanning multiple platforms [dual-source, rapid kVp-switching, dual-layer, photon-counting detector CT (PCD-CT)], protocols, and study designs, remains heterogeneous.^{4,5}

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A 17-study meta-analysis by Monti et al.³ reported pooled sensitivity and specificity for DECT in diagnosing PE of approximately 90%, yet explicitly concluded that DECT did not provide a diagnostic advantage over single-energy CT (SECT). Subsegmental PE was excluded from quantitative pooling because of data heterogeneity, and neither radiation nor contrast doses decreased over time.³ Krasniqi et al.⁶ confirmed that a 45-mL DECT protocol achieved a lower iodine load than 60-mL SECT in 177 patients (92 DECT vs. 85 SECT) without sacrificing diagnostic image quality; however, this was at the cost of more non-diagnostic enhancements (16.1% vs. 5.2%). In contrast, Ferrández-Ferrández et al.⁷ demonstrated in a randomized trial that spectral CTPA with VMI and iodine maps improved vascular attenuation without increasing iodine dosage.

Compared with recent reviews,^{5,8} this article makes three contributions. First, it constructs a three-tier evidence framework

(image quality, diagnostic performance, and clinical outcomes), exposing the fallacy that better images equal better diagnosis. Second, it provides a body mass index (BMI)– and estimated glomerular filtration rate (eGFR)–stratified recommendation table (Table 1) with annotated evidence levels, explicitly characterized as empirical and expert-opinion-based, rather than guideline-grade. Third, it analyzes the overdiagnosis risk of iodine-map-detected isolated subsegmental PE against guidelines and primary empirical data.

The evidence is organized by endpoint tier rather than by technique: image-quality endpoints (Section 2, Tier I), diagnostic performance (Section 3, Tier II), and clinical outcomes (Section 4, Tier III), followed by cross-tier synthesis (Section 5), stratified empirical recommendations (Section 6), limitations with future directions (Section 7), and conclusions (Section 8).

1.1 Literature search strategy and screening process

PubMed (MEDLINE), Embase, Web of Science Core Collection, and the China National Knowledge Infrastructure (CNKI) were searched between January 2016 and June 2026 (last search: June 30, 2026). Two initially ahead-of-print records^{6,9} have since received formal volume and page numbers. The strategy combined medical subject heading terms (“Radiography, Dual-Energy Scanned Projection”; “Pulmonary Embolism”; “Computed Tomography Angiography”) with free-text keywords (“dual-energy CT”, “spectral CT”, “CTPA”, “PE”, “iodine map”, “virtual monoenergetic”). Full eligibility criteria are provided in Supplementary Material 1. Preclinical mechanistic studies were excluded from the diagnostic-evidence synthesis but are cited separately as Oxford Centre for Evidence-Based Medicine (OCEBM) Level 5 evidence where they inform protocol-design rationale (e.g., Zhao et al.¹⁰). Both authors independently screened titles and abstracts; disagreements were resolved by discussion. Complete Boolean search strategies are provided in Supplementary Material 1.

The initial search yielded 1,287 records. After removing 315 duplicates, 972 underwent title and abstract screening, with 729 excluded. Full-text evaluation of the remaining 243 records yielded 26 database-derived studies meeting the predefined criteria; with 2 pre-2016 foundational references added by backward citation tracing,^{11,12} 28 studies were included in total (Figure 1, Supple-

mentary Table 1). The flow diagram borrows presentation conventions from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020¹³ for transparency, without implying systematic-review conduct.

Of the 28 included studies, most are cited individually where they inform specific claims. The 46-item reference list also contains methodological citations,^{13–16} guidelines and consensus statements,^{1–2,17,18} narrative and state-of-the-art reviews retained as background context rather than eligible evidence,^{5,8,19–23} and technical or preclinical investigations cited as OCEBM Level 5 rationale for protocol design.^{10,24} The study by Celtikci et al.²⁵ was added during revision at the reviewer’s request and lies outside the search-derived roster. Eligible studies are itemized in full in Supplementary Table 1.

No meta-analysis was performed, because substantial heterogeneity across DECT platforms, protocols, and endpoints would render pooled estimates misleading. Equally deliberate is the narrative framing, with structured search elements adapted from, but not claiming compliance with, PRISMA 2020:¹³ A search-reporting apparatus was adopted (Boolean strategies, deduplication, screening, and flow accounting; Figure 1, Supplementary Table 1), whereas the defining operations of a systematic review (prospective protocol registration, exhaustiveness auditing, per-study risk-of-bias scoring, and quantitative synthesis) were intentionally not undertaken. The objective is conceptual organization of a heterogeneous field into endpoint tiers rather than pooled estimation, and a narrative architecture with fully traceable lineage is the appropriate vehicle.

2. Tier I. Image-quality evidence: physical gains and their boundaries

Tier I assembles physical image-quality evidence: gains in vascular attenuation, signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) (Sections 2.1–2.2), together with the patient-specific boundaries within which these gains hold (Section 2.3).

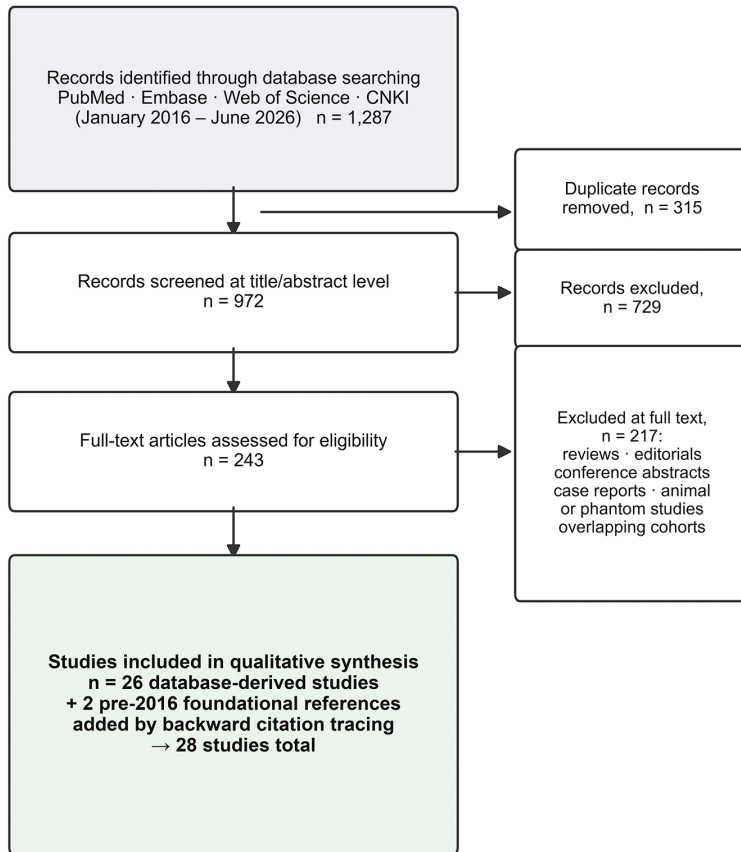
2.1 Vascular enhancement mechanisms of low-keV virtual monoenergetic imaging and low-iodine protocols

Low-keV VMI (25–50 keV) exploits the sharp increase in iodine photoelectric absorption near the iodine K-edge (approximately 33 keV), increasing CT attenuation of iodine-containing blood.^{19,20} Below this range, photon starvation and beam-hard-

Main points

- A three-tier evidence framework (image quality ≠ diagnostic performance ≠ clinical outcomes) is proposed and populated with 28 dual-energy computed tomography (DECT) pulmonary embolism (PE) studies (PubMed/Embase/Web of Science/China National Knowledge Infrastructure, 2016–2026), with the radiomics evidence appraised against CheckList for Evaluation of Radiomics reporting standards.
- Pooled meta-analytic evidence, constrained by heterogeneity and the absence of a stable reference standard, shows no consistent diagnostic advantage of DECT over single-energy CT pulmonary angiography; iodine maps improve detection of distal perfusion defects but require correlation with PE morphology.
- Low-keV virtual monoenergetic imaging at 40–50 keV enables iodine load reduction to approximately 6 g in selected protocols; low-keV image quality is maintained only in patients who are not obese [body mass index (BMI) <30 kg/m²].
- Iodine-map perfusion defects in distal arteries—suspicious for, but not confirmatory of, subsegmental PE—should not alone trigger anticoagulation; clinical probability, D-dimer, and lower-limb venous ultrasound should be incorporated according to the 2019 European Society of Cardiology/European Respiratory Society guidelines.
- A BMI- and estimated glomerular filtration rate–stratified scanning protocol table with Oxford Centre for Evidence-Based Medicine 2011 evidence-level annotations is provided.

Schematic flow diagram of the structured literature search and study-selection process



Flow updated during revision; eligible studies are itemized in Supplementary Table S1.

and complete reporting of reconstruction parameters remains essential for cross-platform comparability.

2.2 Physical principles of iodine density maps and the standardization gap

Iodine density maps rely on iodine-water two-material decomposition, extracting iodine-specific images with suppressed soft-tissue background and enabling “functional CT” in a single acquisition.²⁰ Cross-platform standardization of iodine density values is a core unresolved issue: Limited calibration approaches include the iodine density ratio³³ and single-center scan-rescan testing, but no universal cross-platform phantom or algorithm has been established.³⁴ In particular, iodine density values reported by different DECT platforms are not directly comparable: Dual-layer systems report normalized, unitless iodine-density ratios referenced to an intravascular blood-pool standard,³³ whereas dual-source thresholds are expressed as mass concentrations (e.g., 1.75 mg/mL).³⁵ These ratio-vs.-concentration dimensions preclude direct numeric comparison and reflect vendor-specific algorithms and unit conventions rather than underlying tissue physiology.

2.3 Body mass index stratification and safety boundaries of low-iodine protocols

Patient body habitus influences DECT iodine-map quality. Zhang et al.²⁸ confirmed the feasibility of a low-iodine, low-dose protocol in 90 patients with BMI < 30 kg/m², with 65-keV virtual monoenergetic reconstruction and Adaptive Statistical Iterative Reconstruction-V maintaining image quality. For BMI ≥ 30 kg/m², photon starvation at 40–50 keV limits the SNR; a higher iodine load or higher keV should be considered.^{12,21} The American College of Radiology–National Kidney Foundation consensus¹⁷ distinguishes contrast-associated acute kidney injury (CA-AKI) from contrast-induced AKI (CI-AKI), noting that CI-AKI risk is extremely low at eGFR ≥ 30 mL/min/1.73 m² with current agents (estimated near 0% at eGFR ≥ 45 and 0%–2% at eGFR 30–44). However, no formal safety threshold linking iodine-dose reduction to renal endpoints has been established. This association rests on mechanistic inference rather than outcome-level evidence, and the minimum safe iodine dose for eGFR < 30 remains undefined. Notably, both cornerstone low-iodine protocols enrolled no patients with BMI > 30 kg/m².^{27,28} The < 30 boundary adopted throughout this review therefore mirrors validated populations rather than an

Figure 1. Schematic flow diagram of the structured literature search and study-selection process for this narrative review, drawn following PRISMA 2020 reporting conventions for transparency (not a systematic review). Records were identified from PubMed, Embase, Web of Science, and CNKI (January 2016–June 2026).

ening artifacts increase sharply, establishing 40–50 keV as the practical working range.

Wannasopha et al.⁴ reported a per-location area under the receiver operating characteristic curve (AUROC) of 0.882 for 40-keV VMI+ in 64 patients, although interobserver agreement for the denoised “VMI+” reconstruction ($\kappa = 0.75$) was lower than that for standard CTPA ($\kappa = 0.88$). At 40-keV VMI+, pulmonary trunk attenuation rises to roughly threefold that of linearly blended (LB) reconstructions [e.g., 718 vs. 229 Hounsfield units (HU)].²⁶ Meier et al.²⁷ confirmed non-inferior CNR with a 75% iodine reduction at 40-keV VMI, and Krasniqi et al.⁶ showed in 177 patients that a 45-mL DECT protocol preserved vascular attenuation with significantly higher SNR and CNR than 60-mL SECT.

Reduced-contrast strategies are meaningful only within the low-keV environment: The CNR gain that offsets lower iodine delivery is generated by monoenergetic reconstruction

itself, so low-iodine DECT CTPA must be embedded in virtual monoenergetic acquisition and reconstruction from the outset.^{19–20,26} These reductions carry strict provenance caveats: They derive from cohorts restricted to BMI < 30 kg/m² on defined scanner pipelines, and extrapolation to other platforms, higher BMI, or uncontrolled injection remains unsupported.^{11,27,28}

Acquisition-level choices condition these physical gains. Patient-adaptive bolus triggering improved CNR in the main pulmonary artery and lower-lobe segmental arteries compared with a fixed delay ($P = 0.030$ and $P = 0.002$),⁹ and patient-specific timing frameworks are supported preclinically;¹⁰ spectral protocols maintain diagnostic vascular attenuation even at 20 mL of contrast medium.⁷ Deep-learning image reconstruction and high-pitch photon-counting acquisition partially recover the noise penalty of low-keV imaging,^{29–31} iterative reconstruction preserves diagnostic quality at very low doses,³²

arbitrary cutoff, and the corresponding Table 1 row retains Expert Opinion grading.

3. Tier II. Diagnostic-performance evidence

Tier II moves from physics to observers: detection yield, sensitivity, specificity, and accuracy judged against reference standards, culminating in the contested territory of subsegmental findings.

3.1 Incremental detection by iodine maps in distal arteries

Iodine maps depict pulmonary perfusion defects, not emboli directly; equating perfusion defects with PE without a CTPA morphological correlate is the primary source of overdiagnosis. Subsegmental PE accounts for 3%–12% of CTPA-detected PEs,²¹ and its management remains controversial. Iodine maps aid the detection of distal emboli (Ta-

ble 2). Weidman et al.³⁶ evaluated the incremental value of iodine maps in 1,144 DECT CTPA examinations, reporting 27 additional emboli [21 (77.8%) subsegmental, 24 (88.9%) occlusive] and 11 new PE diagnoses (1.0%; 95% CI, 0.5%–1.7%). Suo et al.³⁵ found that an iodine density threshold of 1.75 mg/mL achieved 92.0% sensitivity and 90.0% specificity for acute PE against the CTPA-based reference standard. Iodine-map hypoperfusion

Table 1. Platform- and patient-characteristic-stratified empirical scanning recommendations for DECT CTPA, with explicit evidence-basis labels and OCEBM annotations

Stratification	Scanning mode	VMI (keV)	Iodine load (g elemental iodine)	Evidence level (OCEBM)	Recommendation strength	Key references	Evidence basis
Normal BMI (< 30), eGFR ≥ 60	Dual-source/dual-layer DECT	40 keV	~6 g iodine (26)	Image quality: 1b (11); Diagnostic: 3 (26-27); Outcome: 5 (expert)	Weak	(11,27,28)	Study-supported
eGFR 30–59 or CM volume reduction indicated	Dual-source DECT (Sn filter)	50 keV	≥15 g	3	Weak	(7,9,28)	Extrapolated
BMI ≥ 30 or obesity	SECT or low-pitch DECT	N/A	≥24 g	3 (6) + 5 (expert opinion)	Expert opinion	(6)	Expert opinion
eGFR < 30 or CM contraindicated	Non-contrast spectral parameters (exploratory; does not replace standard diagnostic workup)	EDM + Zeff (lesion depiction only; cannot exclude PE)	0 g	3 (42,43)	Expert opinion	(42,43)	Extrapolated
Reduced cardiac output*	Patient-adaptive triggering	40 keV	Individualized	3 (9) + 5 (10)	Expert opinion	(9,10)	Extrapolated

Evidence levels follow the Oxford CEBM (OCEBM 2011) system.¹⁶ Empirical protocol (Weak): benefit likely outweighs risk, with limited evidence. Expert opinion: single-center, simulation, or mechanistic evidence; not recommended for routine clinical use. *Reduced cardiac output assessed via thorough clinical evaluation. All recommendations are empirical, not guideline-grade, and have not undergone prospective multicenter validation or Delphi consensus. VMI, virtual monoenergetic imaging; CM, contrast medium; Sn, tin filter; EDM, electron density map; Zeff, effective atomic number; eGFR, estimated glomerular filtration rate; BMI, body mass index; N/A, not applicable. Iodine loads are expressed as grams of elemental iodine; the eGFR 30–59 row reflects reduced-dose protocols vs. a routine 18.5-g iodine standard.²⁸ Low-iodine schemes for eGFR <30 mL/min/1.73 m² lack outcome-safety validation and should not enter routine clinical pathways. Condition mapping of iodine-load tiers to source publications: Approximately 6 g corresponds to the propensity-matched dual-source cohort of the study by Meier et al.,²⁷ which enrolled no patients with BMI ≥30 kg/m². The 18.5-g routine baseline reflects the fixed protocol-A burden of the study by Zhang et al.²⁸ (0.370 g iodine/mL × 50 mL), a study population likewise restricted to BMI < 30 kg/m². Reduced-dose (≥ 15 g) and conventional (≥ 24 g) tiers are author-positioned rather than validated thresholds: The conventional tier reflects standard multidetector CTPA iodine loads above the routine anchor, and neither tier has been validated in outcome studies. The reduced-cardiac-output row extrapolates image-quality gains from adaptive triggering,⁹ supported by preclinical timing work.¹⁰ No tier has been tested prospectively across vendors.

Table 2. Key characteristics of dual-energy computed tomography pulmonary angiography studies across evidence tiers

Study	Design/n	Platform	Iodine load/CM volume	Main findings	Evidence level (OCEBM)
Wannasopha et al. ⁴	Retro/64	Dual-source	Standard	AUROC, 0.882 (Kappa, 0.75 vs. 0.88)	3
Weidman et al. ³⁶	Retrospective/1,144 exams	Dual-source	Routine	Iodine maps: 27 additional PEs (new diagnosis in 1.0% of exams, 11/1,144)	3
Im et al. ³⁹	PSM (propensity score matched)/480	Dual-source	Routine	C-stat: DECT, 0.819 vs. CTPA, 0.759	3
Gertz et al. ³³	Retro/131	DL-DECT	15 g (50 mL)	APE vs. CTEPH AUROC, 0.82	3
Meier et al. ²⁷	PSM (propensity score matched)/82	Dual-source	6 g/15 mL	CNR non-inferior vs. standard protocol	3
Krasniqi et al. ⁶	Observational/177	Dual-source	45 mL	SNR/CNR improvement	3
Gotta et al. ³⁸	Retro/131	Dual-source	Standard	Accuracy, 0.94 (AUROC, 0.91)	3
Monti et al. ³	Meta/17 studies	Mixed	50–325 mL	LB+IM: Sen, 0.89; Spe, 0.90	1a
Abdellatif et al. ⁴¹	Meta/182	Mixed	Not reported	Sen, 0.89; Spe, 0.95	1a
Suo et al. ³⁵	Retro/40	Dual-source	Standard	Iodine density threshold 1.75 mg/mL (dual-source platform)	3

Evidence levels follow the Oxford CEBM (OCEBM 2011) system. Retro, retrospective; Meta, meta-analysis; Observational, observational cohort; Sen, sensitivity; Spe, specificity; AUROC, area under the receiver operating characteristic curve; PSM, propensity score matching; IM, iodine maps; LB, linear blending; CTEPH, chronic thromboembolic pulmonary hypertension. Gertz et al.³³ and Gotta et al.³⁸ both report n = 131 but from different centers and platforms (Cologne dual-layer vs. Frankfurt dual-source).

is moreover non-specific: Transient interruption of contrast, respiratory-motion pseudo-filling defects, beam hardening, and cardiac or parenchymal confounders may each generate defects unrelated to embolism.²³ Anticoagulation decisions should never follow from perfusion appearances alone. Because the Monti et al.³ meta-analysis excluded subsegmental findings from quantitative pooling because of data heterogeneity, its pooled estimates pertain chiefly to central and segmental emboli. Extrapolating them to subsegmental disease would understate peripheral capability, whereas accepting isolated small-series estimates would overstate validated accuracy. Therefore, Monti-derived pooled sensitivities and specificities are treated as applicable to proximal and segmental PE, and subsegmental performance is discussed separately using primary empirical data.³⁵⁻³⁷

3.2 Combined reading strategies and reporting quality gaps

Combined reading translates incremental detection into reliable diagnosis. Leithner et al.²⁶ evaluated three reconstructions in 68 suboptimally enhanced DECT CTPA examinations: M_0.6 alone achieved 69.1% per-segment accuracy. Adding perfusion maps improved accuracy to 86.8%, and adding both perfusion maps and 40-keV VMI+ (protocol 3) reached 92.6% (AUROC, 0.989 vs. 0.874, $P = 0.003$), indicating that the incremental value of iodine maps is most pronounced in suboptimally enhanced examinations. Gertz et al.³³ confirmed in a 131-patient dual-layer cohort (Cologne) that dual-layer DECT distinguishes acute PE from chronic thromboembolic pulmonary hypertension (CTEPH) based on iodine density (AUROC, 0.82), with higher mean and peak iodine uptake in acute PE, normalized to the main pulmonary artery. In a separate 131-patient dual-source cohort (Frankfurt), Gotta et al.³⁸ reported a radiomics accuracy of 0.94 (AUROC, 0.91), representing a distinct study using different hardware despite an identical sample size.

3.3 The subsegmental dilemma: perfusion defects vs. morphological emboli

Whether these additional distal findings should change management remains contested. The 2019 ESC/ERS guidelines grade further confirmatory imaging for isolated subsegmental filling defects as class IIb (level C) and note the absence of robust evidence favoring anticoagulation over watchful waiting.¹ The 2026 AHA/ACC guideline assigns isolated subsegmental PE in patients who

are symptomatic and at low risk to category B1.²

The mismatch between perfusion and morphology is quantifiable. In 43 patients with subsegmental PE scanned on third-generation dual-source DECT, Celticki et al.²⁵ measured lung attenuation, iodine density, and normalized uptake across 81 hypoperfused segments; 45 (55.6%) corresponded to a thrombus visible on CTA, whereas 36 (44.4%) had no morphological correlate. Iodine density and normalized uptake followed a significant stepwise gradient (hypoperfused segments with thrombus < hypoperfused segments without thrombus < normally perfused parenchyma; $P < 0.001$). These data support two complementary interpretations. First, iodine maps detect physiologically real distal abnormalities beyond CTA morphology, consistent with the concern that meta-analytic pooling confined to morphologically confirmed emboli underestimates distal DECT capability.^{3,38} Second, nearly half of iodine-map hypoperfusions lacked a morphological correlate, reinforcing that perfusion defects must not be equated with PE and that management decisions require integration with clinical probability, D-dimer, and venous ultrasound.

4. Tier III. Clinical-outcome evidence

Tier III asks the question that ultimately matters: whether additional imaging information changes risk stratification, management decisions, or patient outcomes.

4.1 Prognostic value of dual-energy computed tomography perfusion metrics vs. right ventricular/left ventricular diameter ratio

A right ventricular/left ventricular (RV/LV) diameter ratio > 1 confers a 2.5-fold all-cause and 5-fold PE-related mortality risk²² and is the most stable CTPA prognostic indicator.^{21,22} The 2026 AHA/ACC guideline recommends numerical RV/LV ratio reporting on CTPA (axial or reformatted four-chamber view), citing a cut point of ≥ 1.0 with sensitivity of 85% and specificity of 72%.²

Im et al.³⁹ compared DECT perfusion defect volume with RV/LV ratio for 30-day mortality in 480 patients with acute PE who were propensity-matched; CTPA- and DECT-based models yielded C-statistics of 0.759 and 0.819, respectively ($P = 0.117$). Relative perfusion defect volume (percentage of total lung volume) was 10.21% [interquartile range (IQR), 6.88–13.87] in the mortality group vs. 7.73% (IQR, 5.04–12.49) in survivors

($P < 0.001$), without exceeding CTPA RV/LV in merged models.

Three features anchor this primacy: formal guideline and Pulmonary Embolism Reporting and Data System, version 2026, (PE-RADS v2026) endorsement as the outcome-validated right-heart surrogate,^{2,18} a direct hemodynamic rationale based on the accompanying pressure-overload signs,¹⁸ and repeated outcome-level testing across scanner generations that no DECT metric has yet undergone.³⁹

The RV/LV ratio and DECT perfusion metrics should be read as complementary components of a single CTPA-derived risk assessment rather than competing tests, potentially refining early triage of patients with normotensive PE; prospective validation is still lacking.

A structured reporting standard now consolidates these elements: PE-RADS v2026.¹⁸ Pulmonary Embolism Reporting and Data System, version 2026, classifies examinations by the anatomic location of the most proximal clot (ordinal categories 0–4, accounting for arterial anatomic variants), attaches image-quality qualifiers down to subsegmental assessability, and adds right-heart and extravascular-extension modifiers; risk stratification integrates hemodynamic status rather than clot burden alone.¹⁸ Within the present framework, its relevance is twofold: It furnishes Tier II morphology with a reporting vocabulary aligned with management triage, and it routes the right-heart signs above as Tier III inputs into everyday reports, standardizing downstream prognostic inference.

4.2 Chronic thromboembolic disease discrimination and management impact

Valizadeh et al.⁴⁰ reported pooled sensitivity of 87.5% and specificity of 91.2% for DECT diagnosis of CTEPH (9 studies; 751 participants; overall AUROC, 0.95); dual-layer DECT likewise separates acute PE from CTEPH perfusion patterns (Section 3.2).³³ Evidence remains limited to small retrospective studies (OCEBM Level 3).

DECT's clinical utility in CTEPH extends beyond diagnostic accuracy: Because chronic and acute embolic disease can coexist and require divergent management (pulmonary endarterectomy vs. anticoagulation), separating anatomic defects from perfusion abnormalities in a single acquisition reduces reliance on ventilation/perfusion (V/Q) scintigraphy or invasive angiography. Iodine maps further help distinguish true vascular

defects from atelectasis- or mosaic-perfusion-related pseudodefects that confound planar CTPA interpretation.⁴⁰ Nevertheless, the absence of a universally accepted iodine-density cut-off for CTEPH, together with the predominance of small retrospective series (OCEBM Level 3), means DECT currently supports rather than supplants conventional confirmation pathways; definitive diagnosis still rests on invasive angiography.^{33,40}

A contemporary comprehensive review consolidates these findings: DECT lung perfusion “has gained widespread recognition” as a valuable tool for identifying perfusion abnormalities, with iodine maps increasing diagnostic confidence for CTEPH identification and reported sensitivity and specificity in single-center series approaching 100% when perfusion imaging is combined with CTPA. Chronic perfusion defects are characteristically wedge-shaped and peripheral, aiding discrimination from the more diffuse abnormalities of emphysema. The same review also notes that insufficient disease awareness among radiologists causes CTEPH misdiagnosis or delayed diagnosis.²³

4.3 Outcome-tier synthesis: incremental prognostic benefit not yet demonstrated

At present, DECT-derived perfusion metrics have not demonstrated incremental prognostic benefit beyond conventional CT variables. The largest comparison to date found no significant difference between DECT- and CTPA-based prognostic models (C-statistics, 0.759 vs. 0.819; $P = 0.117$).³⁹ Tier III therefore operates as a hypothesis-generating layer defining what prospective studies must test—whether perfusion-informed risk stratification changes management or outcomes—rather than as validated clinical value.

5. Cross-tier synthesis, framework implications, and regional evidence

5.1 Image quality ≠ diagnostic performance ≠ clinical outcome

A central finding emerges from the DECT PE evidence: Image-quality gains (CT attenuation, SNR, CNR)^{4,6,28} have not reliably translated into better diagnostic performance

against independent reference standards,^{3,41} and no direct evidence shows that DECT metrics improve patient outcomes compared with SECT.³⁹ In the study by Wannasopha et al.,⁴ attenuation and AUROC gains coexisted with decreased interobserver agreement (Section 2.1), a hypothesis-generating signal limited by the small sample and absence of formal testing. Monti et al.³ concluded that DECT did not surpass SECT for acute PE (pooled sensitivity, 0.87–0.90; specificity, 0.90–0.93). This pattern—attenuation gains that do not translate into diagnostic superiority—is the cornerstone of the three-tier framework (Figure 2).

This framework has direct implications for future DECT research. Image-quality metrics (CT attenuation, CNR) are surrogate endpoints: Higher contrast resolution does not guarantee correct lesion classification, especially when interobserver agreement is imperfect.⁴ Similarly, greater Tier II detection may not improve Tier III outcomes when the additional findings lack evidence-based management pathways. Future DECT PE studies should therefore look beyond im-

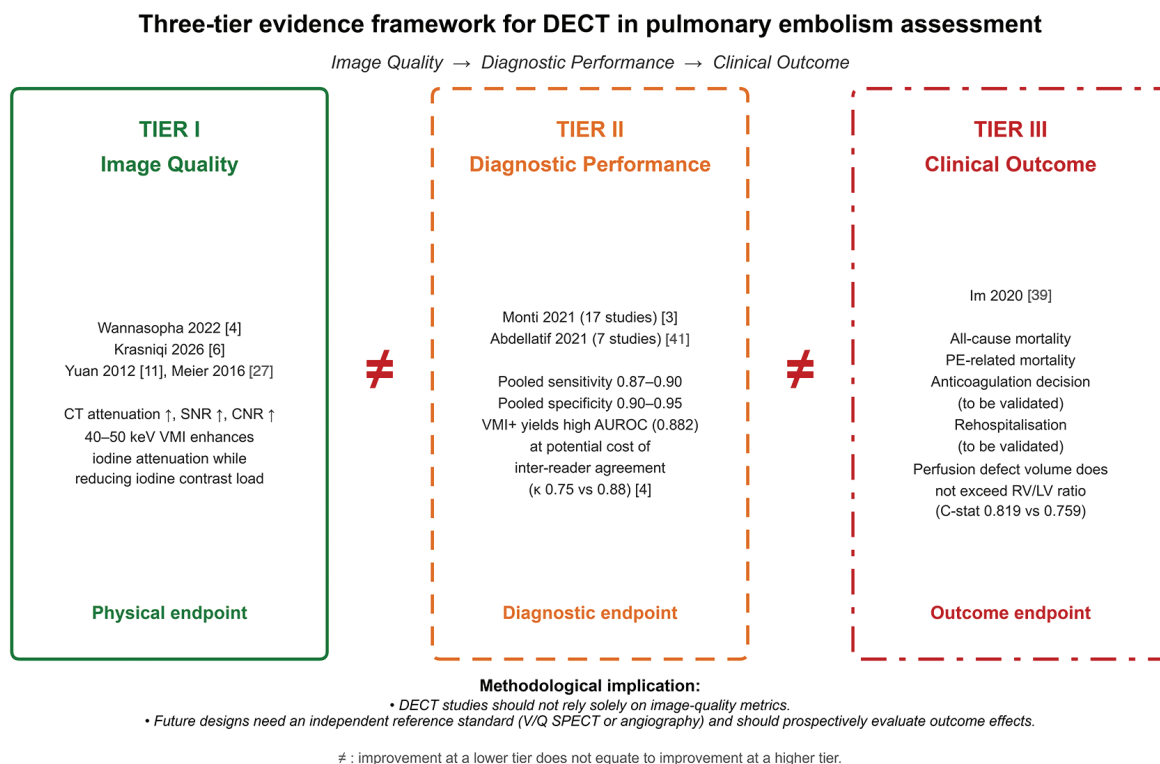


Figure 2. Three-tier evidence framework for DECT in pulmonary embolism assessment. Tier I (Image Quality, physical endpoint): CT attenuation, SNR, CNR. Tier II (Diagnostic Performance): sensitivity, specificity, AUROC. Tier III (Clinical Outcome): anticoagulation decision, rehospitalization, mortality. Evidence supporting Tier I–II: VMI improves CNR and reduces iodine load;^{4,6,11,27} pooled sensitivity of 0.87–0.90 and specificity of 0.90–0.95 for DECT;^{3,41} DECT vs. SECT meta-analyses show no clear diagnostic advantage. Evidence supporting Tier II–III: DECT perfusion defect volume does not exceed the RV/LV ratio (C-statistic: DECT 0.819 vs. CTPA 0.759, $P = 0.117$).³⁹ The red ≠ symbol between tiers denotes that improvement at a lower tier does not equate to direct translation into improvement at a higher tier (limited direct translation). Tier III improvements remain hypothesized pending prospective outcome-level validation. DECT, dual-energy computed tomography; SNR, signal-to-noise ratio; CNR, contrast-to-noise ratio; AUROC, area under the receiver operating characteristic curve; SECT, single-energy computed tomography, RV/LV, right ventricular/left ventricular; CTPA, computed tomography pulmonary angiography.

age-quality metrics: They should incorporate independent reference standards [e.g., V/Q single-photon emission CT (SPECT) or PA] and prospectively test whether changes in detection strategies alter clinical management (e.g., anticoagulation decisions) and patient outcomes.

Relative to established appraisal instruments, the contribution is orthogonal rather than competing. OCEBM ranks studies vertically by design, PRISMA governs process transparency, and the Standards for Reporting of Diagnostic Accuracy polices index-test reporting.¹⁴ None indicates where along the chain from physics to prognosis an individual claim sits: This is the position that the three-tier scheme explicitly assigns. Auditing each statement against its tier therefore exposes silent tier-hopping, such as presenting surrogates as outcomes, at the level of individual assertions, something vertical grading alone cannot reveal.

5.2 Platform heterogeneity and meta-analytic constraints

Cross-tier heterogeneity constrains the translation of DECT's technical promise into practice: Hardware architectures (dual-source, rapid kVp-switching, dual-layer, photon-counting) and post-processing software differ substantially (Table 3). Vendor-specific VMI algorithms, iodine-map methods, and units are not interchangeable;²⁰ evidence from different platforms cannot be aggregated. In the study by Monti et al.,³ volumetric CT dose index ranged from 4 to 20 mGy (median, 9 mGy), and total iodine volume ranged from 50 to 325 mL (median, 80 mL). Subgroup analysis showed the following: LB images alone (6 study parts, 348 patients) yielded pooled sensitivity of 0.87 and specificity of 0.93; LB plus iodine maps (14 study parts, 1,007 patients) yielded 0.89 and 0.90, respectively; and LB plus iodine maps plus VMI (2 studies, 144 patients) yielded 0.90 and 0.90, respectively. These estimates reflect accuracy against composite reference standards rather than direct head-to-head comparisons with SECT.^{19,24,42} Abdellatif et al.,⁴¹ in a separate meta-analysis (7 studies, 182 patients), reported pooled sensitivity of 0.89 and specificity of 0.95 (AU-ROC, 0.935).

Many included studies also received manufacturer support (Siemens, GE, Philips), adding funding-related bias to device-level heterogeneity.

5.3 Regional evidence: Chinese-language core literature

Six Chinese-language studies^{29,34,35,37,43,44} offer regional evidence: Liu et al.³⁴ tested low-iodine subtraction CTPA with iodine maps in 48 patients vs. SPECT/CT (sensitivity, 91.7%; specificity, 99.1%; 100% segmental, 66.7% subsegmental). Wu et al.⁴³ used non-contrast dual-layer spectral CT parameters in 52 patients, with electron density map (EDM) and EDM-plus-effective atomic number fusion achieving acute PE detection rates of 54.7% and 69.8%. Xie et al.⁴⁴ achieved 97.6% acute PE detection with non-contrast dual-layer spectral CT. Yang et al.²⁹ validated deep-learning image reconstruction in 60 patients with a reduced iodine load (35 mL vs. 45 mL), improving pulmonary artery attenuation (635.62 vs. 469.54 HU, $P = 0.001$). Yan et al.³⁷ showed in 62 patients in a retrospective study that single-source rapid-kVp-switching iodine maps detected more distal grade 5–7 emboli than monoenergetic images. Suo et al.³⁵ proposed the 1.75 mg/mL iodine density threshold detailed in Section 3.1. These six studies add platform- (subtraction, dual-layer, single-source, dual-source) and patient-diverse data.

5.4 Evidence gaps and current positioning of photon-counting detector computed tomography and artificial intelligence radiomics

Preliminary PCD-CT data indicate approximately 48% radiation reduction and full-cohort spectral acquisition without anatomic region preselection.^{31,45,46} Pannenbecker et al.^{45,46} showed that PCD-CT achieves high image quality for PE detection, with 60-keV photon-counting scans rated best⁴⁵ and excellent or good image quality in 96.1% of PCD-CTPAs vs. 50.9% of energy-integrating detector CTPAs,⁴⁶ albeit with asymmetric reconstruction comparisons. However, more sensitive detection of small emboli has not been linked to improved clinical outcomes, carrying the same overdiagnosis risk as iodine maps. Artificial intelligence (AI) radiomics for PE³⁸ remains exploratory: Few studies meet the CheckList for Evaluation of Radiomics (CLEAR) reporting standards,¹⁵ and no validated multicenter model is yet suitable for clinical adoption.

6. Empirical scanning recommendations stratified by patient characteristics

Platform- and patient-characteristic-stratified recommendations are presented (Figure 3, Table 1). Every row carries an explicit

evidence-basis label: Study-supported (directly demonstrated in clinical studies within the stated population and platform), Extrapolated (derived from related evidence without direct validation of the specific application), or Expert Opinion. Recommendation strength is divided into Weak (benefit likely outweighs risk, with limited evidence) and Expert Opinion (single-center retrospective or mechanistic evidence, not a clinical recommendation). Evidence levels follow the OCEBM 2011 system:¹⁶ 1a = meta-analysis, 1b = randomized controlled trial (RCT), 3 = non-randomized/retrospective, and 5 = mechanistic/simulation/animal. These recommendations represent the authors' interpretation and are offered for reference only, not as practice guidelines. Correspondence to the three-tier framework is as follows: The normal-BMI/eGFR scheme maps to Tier I (image quality), based on CNR evidence from low-keV VMI; the high-BMI or reduced-cardiac-output scheme, lacking Tier II validation, is downgraded to Expert Opinion; the eGFR < 30 non-contrast scheme rests solely on single-center exploratory data with no established tier and should not enter routine clinical pathways. In particular, the approximately 6-g row reproduces conditions validated only in low-BMI cohorts on named scanner families and must not be generalized across platforms or body habitus.

Table 1 footnote: reference 7 (Ferrández-Ferrández et al.⁷) is an RCT (OCEBM Level 1b) evaluating spectral CTPA; it is cited as general supportive evidence in the eGFR-stratified rows and was not conducted in an eGFR-specific cohort, so the row-level evidence rating remains 3.

Applying these recommendations requires matching the patient to the appropriate tier before scanning. For patients with BMI ≥ 30 or eGFR < 30, the imaging benefit of any low-iodine adaptation must be balanced against reduced robustness of iodine-map and perfusion metrics, as well as the absence of established Tier II validation. Pretest probability and clinical gestalt should drive protocol choice: When the probability of PE is low, the protocol should support or exclude the clinical assessment rather than overcall defects that subsequently trigger anticoagulation.

7. Limitations and future directions

This review has limitations. (Methodological) First, as a narrative review, we did not perform quantitative synthesis or protocol preregistration [the structural rationale for

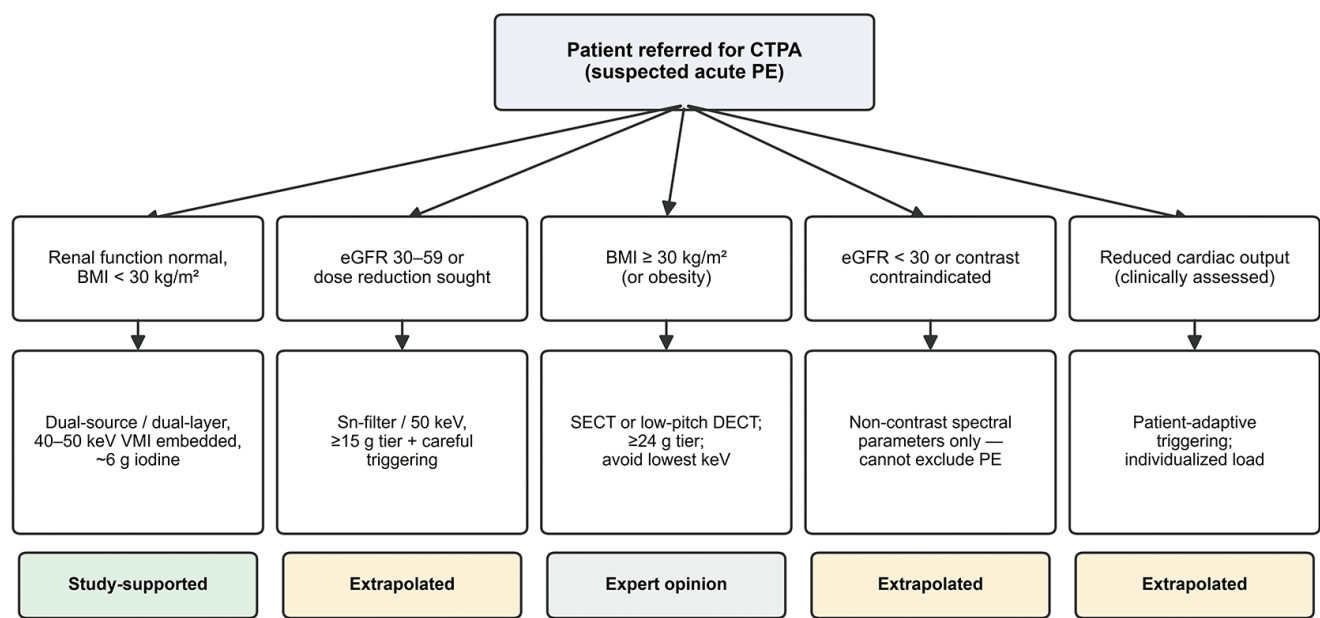
declining Quality Assessment of Diagnostic Accuracy Studies 2 (QUADAS-2)/Grading of Recommendations Assessment, Development, and Evaluation [GRADE] follows below]. Second, the search lacked additional database coverage (Cochrane, Wanfang, VIP). Third, publication bias was assessed qualitatively (below) rather than formally; screening concordance (Cohen's κ) was not computed. Fourth, several key studies had single-center, small-sample, retrospective designs.^{35,36,44} (Evidence-level) Despite OCEBM annotations (OCEBM 2011),¹⁶ the evidence base is dominated by single-center retrospective studies, and recommendations draw on pre-2016 foundational references^{11,12} and a single guideline not specific to DECT² for compar-

ative context. (Cross-platform) Because most studies were platform-specific, generalizability across scanner manufacturers remains unverified; only limited cross-platform head-to-head validation has been published.^{37,42}

A formal QUADAS-2 or GRADE pass was consciously not attempted, for a structural rather than practical reason: Such instruments presuppose a shared index-test/question pair across primary studies, whereas the present roster spans image-quality physics, diagnostic accuracy, and prognostic modeling whose comparators differ fundamentally—consensus image-quality reads, composite clinical standards, and mortality models. Applying one template would manufacture

false comparability, whereas our objective is tier mapping rather than pooled estimation. Instead, a structured qualitative inventory follows. Tier I: Recurring manufacturer funding and prototype-vs.-legacy comparisons (Section 5.2) plausibly inflate attenuation and noise advantages; enrolment was usually consecutive, but sample sizes were small. Tier II: Reference standards are composite and seldom centrally adjudicated. Spectrum effects arise where cohorts preselect suboptimal enhancement²⁶ or where iodine maps were available to the readers generating final diagnoses.³⁶ Positive incremental-yield results predominate in the published record, so publication bias plausibly favors inflated detection gains, although sparse, heteroge-

Simplified scanning-pathway decision diagram (companion to Table 1)



Color legend: ■ study-supported ■ extrapolated ■ expert opinion All pathways empirical — not guideline-grade; condition mapping in Table 1.

Figure 3. Simplified multilevel decision diagram summarizing the empirical scanning pathways of Table 1. Color encodes the evidence basis: green, study-supported; amber, extrapolated; gray, expert opinion. Recommendation strength and safety caveats are not color-encoded and remain governed by Table 1.

Table 3. Comparison of dual-energy computed tomography hardware platforms for pulmonary angiography applications					
Platform	Representative Systems	FOV/Spectral Efficiency	PE Application Suitability	Evidence Level (OCEBM)	Suitable Population
Dual-source (Siemens)	SOMATOM Force/Drive	26–35 cm; high spectral efficiency (19–20)	Optimal CNR at 40 keV; VMI+ with denoising; largest published clinical evidence base	3	BMI <30, normal renal function
Rapid kVp switching (GE)	Revolution CT	50 cm; ~35% spectral efficiency (19–20)	Largest FOV; high temporal resolution; suitable for emergent PE	3	Any BMI, emergent scanning
Dual-layer detector (Philips)	IQon Spectral CT	50 cm; 22–45% spectral efficiency (19–20)	Retrospective spectral analysis; single-phase DECT; suitable for incidental PE detection	3	Renal impairment, retrospective analysis
Photon-counting detector CT (Siemens)	NAEOTOM Alpha	50 cm; intrinsic spectral acquisition	Radiation dose reduced ~48%; full-cohort spectral coverage; limited clinical PE data	3	All populations (research/advanced)

Data adapted from Goo and Goo.²⁰ All evidence levels are Oxford CEBM Level 3. PCD-CT examples are representative Siemens systems; PCD-CT platforms from other vendors are emerging. FOV, field of view; CNR, contrast-to-noise ratio; PBV, pulmonary blood volume; VMI, virtual monoenergetic imaging; PCD-CT, photon-counting detector computed tomography; DECT, dual-energy computed tomography.

neous data preclude formal asymmetry testing. The CTEPH meta-analysis, whose authors employed funnel plots, illustrates what denser data would permit.⁴⁰ Tier III: Retrospective propensity designs³⁹ retain residual-confounding and survivorship-selection vulnerability. This inventory directly motivates the Study-supported/Extrapolated/Expert-Opinion labels of Table 1 and the per-study limitation entries in Supplementary Table 1.

Beyond study-level biases, two coverage constraints bound this synthesis. Review articles were excluded from the eligible roster by construction, so consensus material circulating chiefly in review form, including the reporting framework,¹⁸ informs context but cannot be quantitatively synthesized. Photon-counting evidence originates almost entirely from a single vendor platform,^{30,34,46} with AI and radiomics applications still exploratory (Section 5.4); cross-manufacturer spectral behavior remains uncharacterized. Finally, the Cochrane Library and additional Chinese databases (Wanfang, VIP) were not searched; language restriction to English and Chinese and concentration on CNKI for regional literature may have resulted in additional regional records not being identified elsewhere.

Future research should prioritize (1) prospective multicenter RCTs of DECT low-iodine strategies, (2) cross-platform standardization of iodine-density units and VMI energy selection, (3) PCD-CT clinical outcome validation, and (4) AI–radiomics with CLEAR-compliant reporting.¹⁵

8. Conclusion

In summary, the three-tier framework positions DECT CTPA primarily as a tool for reducing iodine load and improving distal vascular depiction while preserving image quality. It has not demonstrated improved overall diagnostic performance or patient-important outcomes compared with SECT. Because distal iodine-map abnormalities are suspicious findings rather than morphologically confirmed subsegmental emboli, they should be weighed alongside clinical probability, D-dimer, and lower-limb venous ultrasound, warranting caution before anticoagulation. Low-iodine DECT applies only to populations and platforms validated in published studies; broader adoption requires prospective multicenter confirmation of diagnostic consistency and net benefit across BMI and renal-function strata. More broadly, the framework exemplifies a general principle: Surrogate endpoints

must not be equated with patient-important outcomes—a template for any technology whose added information awaits proof of clinical value—while every tabulated protocol remains bound to its validating scanner family and stratum.

Footnotes

Conflict of interest disclosure

The authors declared no conflicts of interest.

Supplementary Table Link: <https://d2v96fxpocvxx.cloudfront.net/a6c507d0-c298-4e01-9874-771986926d20/content-images/20bdd305-e8f0-4a33-b93b-6284fb6fac2a.pdf>

Supplementary Material Link: <https://d2v96fxpocvxx.cloudfront.net/e399ea47-50d3-4ee4-9976-1a9dc17bbe01/content-images/4dd8e960-e725-4f25-bb03-1058182612e5.pdf>

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