



# Dual-Energy CT for Pulmonary Embolism: Current and Evolving Clinical Applications

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Pulmonary embolism (PE) is a potentially fatal disease if the diagnosis or treatment is delayed. Currently, multidetector computed tomography (MDCT) is considered the standard imaging method for diagnosing PE. Dual-energy CT (DECT) has the advantages of MDCT and can provide functional information for patients with PE. The aim of this review is to present the potential clinical applications of DECT in PE, focusing on the diagnosis and risk stratification of PE.

**Keywords:** *Dual-energy computed tomography; Pulmonary embolism; Iodine; Pulmonary artery sarcoma; Chronic thromboembolic pulmonary hypertension*

## INTRODUCTION

Pulmonary embolism (PE) is a potentially fatal disease with varying clinical presentations. It is the third most common cause of death in the United States. It can have a fatal prognosis if the diagnosis or treatment is delayed. Accordingly, prompt diagnosis, in turn allowing for prompt treatment, can dramatically reduce the mortality rate [1-5].

Currently, multidetector computed tomography (MDCT) is considered the standard imaging modality for diagnosing PE [6]. Technical advancements in CT in the past decade have allowed physicians to obtain images of higher quality, with exposure to lower levels of radiation, which demonstrate small subsegmental pulmonary artery (PA) embolisms [7,8]. CT has high diagnostic accuracy in detecting PE [9-12]. It is the most clinically important imaging modality for evaluating patients with PE. In addition, it can provide

crucial information on the hemodynamic stability and prognosis of patients with acute PE [13-15].

Dual-energy computed tomography (DECT) can provide both morphological and functional pulmonary information of the lung in a single contrast-enhanced examination. It has the advantages of MDCT and uses X-rays with two different energy spectra to detect specific substances according to the material decomposition theory [16,17]. This enables selective visualization of the iodine components in tissues. It has recently been actively applied in patients with PE owing to the simultaneous demonstration of pulmonary emboli occluding the PA and resultant perfusion defects in the lung parenchyma [18-20]. This may yield more information about the burden of PE because both perfusion and angiographic images are obtained without increasing the radiation dose. Thus, DECT is a feasible option for the evaluation of PE [21,22].

The aim of this review is to discuss the potential clinical applications of DECT in PE, focusing on the diagnosis and risk stratification of PE.

## Diagnosis of PE Based on DECT: Can DECT Increase the Diagnostic Accuracy of PE?

DECT is useful for detecting acute PE [20,22-25]. The main strength of DECT is that it can show perfusion defects in the lung parenchyma caused by PA occlusion and enable

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direct visualization of filling defects in the PAs [26,27]. The iodine map provides a quick approach to perfusion defects and enables quantitative analysis of the volume of perfusion defects. The quantitative assessment of pulmonary perfusion strongly correlates with pulmonary perfusion scintigraphy and single-photon emission CT (SPECT) images [28,29].

Many small-scale studies have reported the diagnostic value of DECT for the detection of acute PE. The reported sensitivity and specificity range from 60% to 90% and 88% to 99%, respectively [24,25,27,29-32]. In chronic PE, DECT has 96–100% sensitivity and 76–96% specificity using SPECT or scintigraphy as a reference [33,34].

Recent studies have focused on the added values of DECT over CT pulmonary angiography (CTPA) [26,35]. In their study, the diagnostic accuracy of CTPA (85.5–90.4%) improved for both readers with a combination of color-coded lung-perfused blood volume images (95.6–97.6%) with high interobserver and intraobserver agreements (Table 1) [35]. Moreover, the addition of DECT to CTPA improved the detection of peripheral intrapulmonary clots [35]. Small peripheral clots are occasionally difficult to distinguish from the surrounding segmental or subsegmental pulmonary arteries on MDCT. However, DECT is useful for identifying regional iodine perfusion defects due to small clots (Fig. 1). In a recent large-scale retrospective study involving 1035 consecutive patients, a DECT iodine map helped to detect small (segmental or subsegmental) pulmonary emboli in 1% of additional patients [26]. In addition, the DECT technique can improve the image quality even with a small amount of contrast agent (Fig. 2). Using monoenergetic image reconstruction, the vessel attenuation and contrast-to-noise ratio can be improved [36]. This means that when using DECT in PE imaging, the amount of iodine contrast can be reduced, while still maintaining adequate image quality with a high diagnostic confidence.

A recent study reported that deep learning-based automatic lung lobe segmentation and quantitative lobar or zonal perfusion analyses are useful in PE detection, although the study had a small sample size of 88 patients [37]. Further large-scale studies are needed to assess whether deep learning-based quantitative lobar perfusion parameters can provide complementary diagnostic or prognostic information in patients with PE undergoing DECT.

## Ventilation CT Using DECT in PE

Many studies have reported the usefulness of xenon-

enhanced ventilation CT in patients with pulmonary disease [38-40]. Ventilation/perfusion imaging using DECT can visualize the ventilation/perfusion match or mismatch in patients with suspected PE. Xenon is a radiodense gas with a high atomic number of 54, similar to iodine (atomic number: 53). It exhibits photoelectric absorption properties similar to iodine and can therefore be isolated from lung tissues using the material decomposition method.

A previous study performed DECT ventilation/perfusion imaging in 32 patients with suspected PE. Of the 32 patients, six reported mild adverse events (i.e., shortness of breath, mild dizziness, and limb numbness). DECT lung ventilation/perfusion imaging was successfully conducted in 10 patients with PE, and a PE-related ventilation/perfusion mismatch was found in eight patients. The authors concluded that DECT lung ventilation/perfusion imaging could provide high-spatial-resolution information on morphological and functional ventilation/perfusion of the lungs in patients with suspected PE [41].

However, because the atomic number of xenon is close to that of iodine, xenon cannot be distinguished from iodine. Therefore, perfusion and ventilation imaging using iodine and xenon cannot be performed using a single imaging procedure. In their study, 5 minutes after the xenon-enhanced DECT imaging examination, dual-energy CTPA was performed [41]. Therefore, in another study, alternative inhaled contrast agents were suggested for simultaneous ventilation-perfusion imaging for PA-occlusive diseases. In a preclinical study, a ventilation-perfusion evaluation method using krypton (atomic number: 34) and iodine was suggested [42]. Although ventilation scans obtained with xenon or krypton are limited to use in research, they have the potential to become a non-invasive tool for examining the anatomical structures of the lungs and lung ventilation.

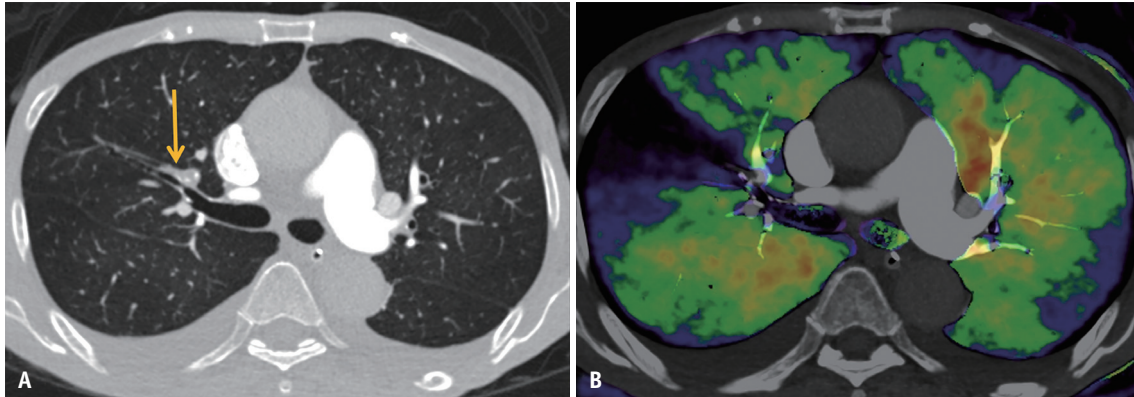
## DECT for Differentiation of PE and PA Sarcoma

PA sarcoma is a rare type of malignancy that arises from the intima or media of the PA and is frequently misdiagnosed as a PE because clinical symptoms and radiological findings are often similar. Early diagnosis and radical resection of PA sarcomas are crucial for survival. Therefore, it is important to clinically differentiate PA sarcomas from PE. CT is an imaging modality that allows for the differential diagnosis of PA sarcoma and PE. It can help differentiate PA sarcoma from PE by visualizing extraluminal tumor extension, expansion of the involved

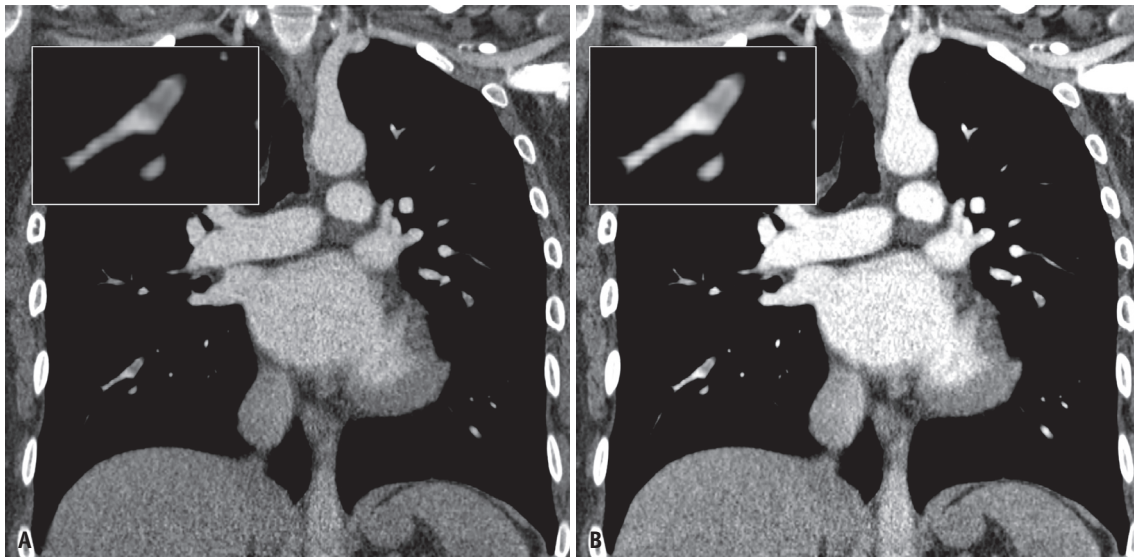
**Table 1. Diagnostic Accuracy of Dual-Energy CT for Patients with Pulmonary Embolism**

Reference	Design	Disease	Patient	PE Patients	CT	Reference Standard	Test (Per-Patient Analysis)	Sensitivity (%)	Specificity (%)	Test (Per Lobe)	Sensitivity (%)	Specificity (%)	Test (Per Segment)	Sensitivity (%)	Specificity (%)
Fink et al. 2008 [25]	Prospective	Acute PE	24	4	Siemens	CTPA	CTPA	100	100	N/A	N/A	N/A	Iodine map (reader 1)	66.7	99.8
Thieme et al. 2008 [29]	Prospective	Acute/chronic PE	13	6 acute, 7 chronic PE	Siemens	Ventilation/perfusion scintigraphy	Iodine map	75	80	N/A	N/A	N/A	Iodine map (reader 2)	60	99.5
Zhang et al. 2009 [85]	Prospective	Suspected for PE	31	17	Siemens	CTPA	Iodine map	93.8	93.3	Iodine map	93.2	94.7	Iodine map	76.1	97.6
Zhang et al. 2009 [27]	Animal study	Acute PE	6 rabbits	6	Siemens	Histopathology	CTPA	90.9	93.3	CTPA	67	100	CTPA	89	92
Lee et al. 2011 [86]	Retrospective	Suspected for PE	309	21	Siemens	Reader 1 (Combining all information from CTPA DECT and software)	CTPA + PBV	95.5	93.3	Iodine map	89	92	Iodine map	89	92
Chai et al. 2012 [31]	Animal study	Acute PE	24 rabbits	24	Siemens	Histopathology	CTPA + PBV	90.9	100	CTPA	98	100	CTPA	100	95
Geyer et al. 2012 [24]	Retrospective	Suspected for acute PE	14	5	GE Healthineers	CTPA	Iodine map	80	88.9	Iodine map	100	95	Iodine map	40	97.6
Wu et al. 2012 [30]	Retrospective	Suspected for PE	53	19	GE Healthineers	CTPA	CTPA	82.8	87	CTPA	82.8	87	Iodine map	93.6	94.2
Okada et al. 2015 [35]	Retrospective	Suspected for acute PE	83	30	Siemens	CTPA or PBV + clinical/physical findings	CTPA	82.8	87	CTPA	82.8	87	CTPA	93.1	100
Zhang et al. 2018 [87]	Prospective	Suspected for acute PE	50	46	Siemens	Emergent DSA angiography	DEPI + CTPA	89.1	75	DEPI + CTPA	89.1	75	DEPI + CTPA	89.1	75
Nakazawa et al. 2011 [88]	Prospective	Chronic PE	51	51	Siemens	Perfusion scintigraphy	Perfusion scintigraphy	100	96.2	Perfusion scintigraphy	100	96.2	Perfusion scintigraphy	100	96.2
Dournes et al. 2014 [33]	Retrospective	CTEPH	40	14	Siemens	Ventilation/perfusion (V/Q) scintigraphy	CTPA	100	92	CTPA	100	92	CTPA	96	76
Masy et al. 2018 [89]	Retrospective	CTEPH	80	36	Siemens	Multidisciplinary expert decisions	Iodine map	100	86	Iodine map	100	86	Iodine map	97	86

CTEPH = chronic thromboembolic pulmonary hypertension, DECT = dual-energy CT, DEPI = dual-energy lung perfusion imaging, DSA = digital subtraction angiography, PA = pulmonary angiography, PBV = perfused blood volume, PE = pulmonary embolism



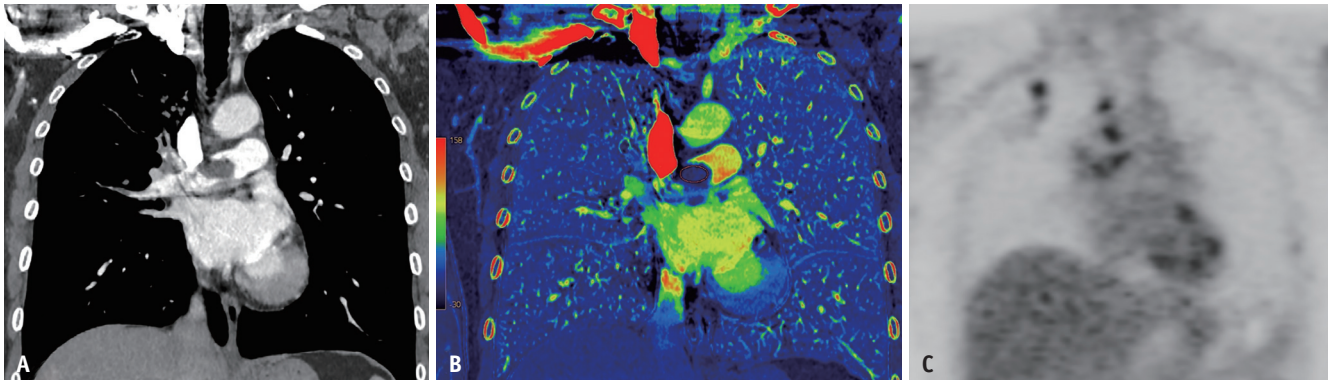
**Fig. 1. A 76-year-old female diagnosed with acute pulmonary thromboembolism.**  
**A.** CT angiography showing a focal filling defect in the right upper lobar pulmonary artery (arrow) due to acute pulmonary thromboembolism and bilateral pleural effusion. **B.** The fusion image of CT angiography and a color-coded iodine map showing a thrombus in the right upper pulmonary artery as well as a corresponding wedge-shaped perfusion defect in the right upper lobe.



**Fig. 2. A 30-year-old female diagnosed with acute pulmonary thromboembolism.**  
**A.** The conventional image with 100 kVp showing a focal filling defect in the right lower subsegmental artery. **B.** A monoenergetic image with 60 keV better depicting a subsegmental thrombus in the right lower lobe.

arteries, or a low-attenuation filling defect of the proximal or main PA. However, these findings might not appear in early-stage PA sarcoma, and in cases of extensive PE, the imaging findings can be similar. Because a dual-energy technique allows iodine to be differentiated from other materials, DECT can help differentiate PE and PA sarcoma by detecting subtle lesion enhancements (Fig. 3). A previous study compared quantitative parameters of DECT between 19 PE and six PA sarcoma cases and found no difference in CT Hounsfield units (HU) (PE vs. PA sarcoma:  $45.5 \pm 15.9$  HU vs.  $47.1 \pm 9.2$  HU;  $p = 0.776$ ), but a significant difference in the iodine concentration measured on an iodine map (PE vs. PA sarcoma:  $0.6 \pm 0.4$  mg/mL vs.  $1.5 \pm$

$0.6$  mg/mL;  $p = 0.001$ ) [43]. These findings showed the possibility that quantification of iodine values using DECT could help differentiate PE from PA sarcoma. Generally, fluorodeoxyglucose (FDG) PET-CT is a useful method to distinguish PA sarcoma from PE based on FDG uptake with a difference in the maximum standard uptake value [44-47]. However, PE can have varying uptake, which results in difficulties in differentiating it from PA sarcoma [48,49]. DECT has the added roles of specific tissue characterization, clear anatomical delineation, and simultaneous evaluation of lung perfusion [43].



**Fig. 3. A 58-year-old female with pulmonary artery sarcoma.**

**A.** A coronal contrast enhanced CT image showing an intraluminal mass with an eccentric filling defect in the right main pulmonary trunk. **B.** On a coronal color-coded iodine (water) image from dual-energy CT, the mean iodine concentration within the region of interest is 2.6 mg/mL. **C.** A coronal PET image showing focal fluorodeoxyglucose uptake in the intraluminal mass and right upper paratracheal lymph nodes.

### DECT in Assessing Severity and Predicting the Prognosis of Patients with PE

Risk stratification is important in patients with PE because optimal management, monitoring, and therapeutic strategies depend on prognosis. Many CT parameters have been proposed as potential predictors of PE severity and clinical outcomes [14,15,32,50,51]. Among them, the quantitative CT parameter of right ventricular (RV) dysfunction, or an abnormally increased ratio between the RV and left ventricular (LV) diameter in transverse CT sections, is proposed as a strong predictor of adverse clinical outcomes in patients with acute PE [15].

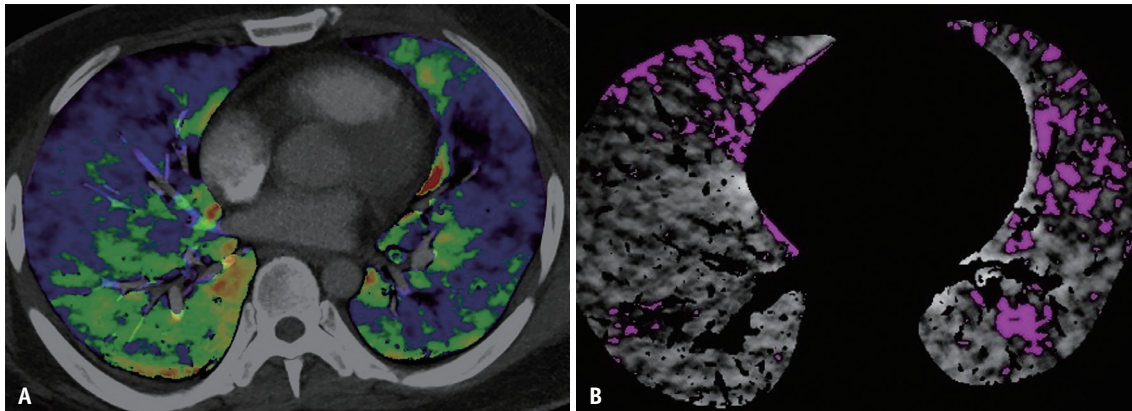
Recently, DECT has been performed for severity assessment and prediction of clinical outcomes in patients with PE [52,53]. Several studies have shown the feasibility of DECT to assess perfusion defects in pulmonary blood volume (PBV) caused by PE [35,37]. Although data are limited regarding the functional relevance of perfusion changes detected with DECT, a few studies have shown a higher rate of right-heart strain among patients with acute PE presenting with a greater extent of perfusion defects on DECT. Previous studies have also shown that the extent of perfusion defects on DECT correlates with adverse clinical outcomes among patients with PE [52,53].

The perfusion defect score calculated using DECT has been suggested as a new imaging biomarker for severity assessment in patients with PE. In a previous study, perfusion defect scores based on DECT scans were used to assess the severity of PE in 30 patients, and the scores were found to correlate well with the RV/LV diameter ratio ( $r = 0.69$ ,  $p < 0.001$ ) and PA obstruction score ( $r = 0.87$ ,

$p < 0.001$ ) [54]. In another study involving 55 patients with PE [55], perfusion defect scores calculated using DECT significantly correlated with the CTPA obstruction score and RV/LV ratio ( $r = 0.62$  and  $0.60$ , respectively,  $p < 0.001$ ) and effectively differentiated between the low- and intermediate-risk groups ( $p = 0.011$ ) [55]. Recently developed software provides a quick automated quantification of pulmonary perfused blood volume, which correlates well with the severity of PE [56].

A pilot study suggested that the volume of the lung with perfusion defects measured using DECT may be used not only as a surrogate marker, but also as a prognosticator of right heart strain in patients with acute PE [52,53]. Another study involving 60 patients with PE reported that the extent of perfusion defects measured on a DECT iodine map is a predictor of adverse clinical outcomes (death or intensive care treatment within 60 days). A multicenter retrospective study involving 115 patients with suspected PE without a detectable thromboembolic clot found that the volume of the lung with perfusion defects is a predictor of patient prognosis [57].

Based on previous studies, quantitative DECT parameters have the potential to be used as prognostic markers in acute PE (Fig. 4) [52,53]. However, existing studies were performed with small groups of participants and lacked the additional effectiveness of perfusion defect quantification with DECT compared to the CT ventricular diameter ratio, which is a well-established and widely used prognostic indicator. In addition, the value of quantitative DECT parameters for prognosis and risk stratification in acute PE is controversial. A recent study involving 172 patients with acute PE demonstrated that while the RV/LV ratio predicted



**Fig. 4. A 34-year-old male with acute pulmonary embolism.**

**A.** A color-coded iodine map showing multifocal perfusion defects in both upper lobes due to pulmonary thromboembolisms. **B.** A map obtained with a volume analysis software showing a perfusion defect volume, measured from -1024 to -1 Hounsfield units, of 324.15 cm<sup>3</sup> and a relative perfusion defect volume of 10.24%.

30-day mortality (hazard ratio, 3.8;  $p = 0.002$ ) and PE-related death (hazard ratio, 18.1;  $p < 0.001$ ), perfusion defects detected using DECT had no added benefit for predicting 30-day mortality over the RV/LV ratio [58]. We conducted a propensity score-matched study to compare the predictive value of quantitative DECT parameters and CT ventricular diameter ratio in patients with acute PE. The propensity-matched study population included 240 patients with acute PE in the CTPA group and 240 patients with acute PE in the DECT group. According to the results, lung perfusion defects measured with DECT had no added benefit over the CT RV/LV ratio alone for prediction of death within 30 days (C-statistics: 0.80, 0.83,  $p = 0.097$ ) [59]. Currently, the data do not prove any additional benefit of functional lung assessment with DECT to predict death from PE [59]. Therefore, larger trials with longer follow-up periods should be performed to estimate the potential influence of DECT findings on treatment strategies to optimize the treatment and outcome of patients with acute PE.

### DECT and Chronic PE and Chronic Thromboembolic Pulmonary Hypertension (CTEPH)

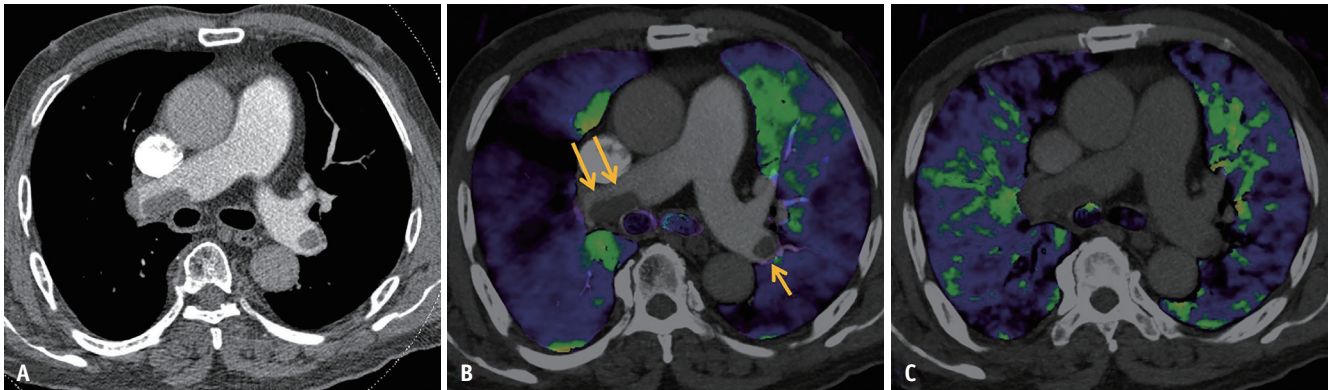
If acute PE does not dissolve over time, it can result in chronic PE. Once emboli attain a chronic organized status, secondary hemodynamic changes develop, eventually causing chronic pulmonary hypertension, followed by right heart failure. This progressive course can be corrected using surgical pulmonary thromboendarterectomy. Therefore, differentiating between acute and chronic emboli is important when pulmonary emboli are detected on CT

images.

Chronic PE has a different perfusion pattern from acute PE because systemic collateral circulation increases to sustain lung tissues distal to the occluded pulmonary arteries (Fig. 5). DECT is useful for demonstrating different perfusion patterns between acute and chronic PE. In a previous study, two-phase DECT was performed in 42 patients with PE, and iodine-related attenuation (IRA) change ratios were calculated using the formula  $100\% \times ([\text{IRA of delayed phase}] - [\text{IRA of PA phase}]) / [\text{IRA of PA phase}]$ . IRA change ratios for patients with acute PE and those with chronic PE were -3.14% and 191.9% ( $p < 0.001$ ), respectively, indicating that delayed enhanced patterns were observed in chronic PE segments. This may be because extensive systemic collateral formation occurs in chronic PE via the bronchial arteries [60]. These results demonstrated that DECT can display iodine distribution to reflect perfusion patterns [61].

In addition to evaluating parenchymal perfusion defects, DECT data are useful for the detection and tissue characterization of intravascular thrombotic material using the material decomposition method, thus differentiating between acute and chronic PE. Kim et al. [62] compared HU, iodine-related HU (HU from monochromatic 70 keV images, HU from mass spectroscopy imaging), and iodine concentration of embolism between 15 patients with acute PE and 11 patients with chronic PE. They found that chronic PE had a significantly higher mean HU, iodine-related HU, and IC compared to acute PE. This may be because the fibrotic components of a chronic thrombus have a greater vascular supply compared to acute thrombi.

Chronic thromboembolic pulmonary hypertension



**Fig. 5. A 60-year-old male diagnosed with chronic pulmonary thromboembolism.**

**A.** CT angiography image showing organized thrombi in both the main pulmonary arteries. **B.** In the pulmonary artery phase, a fusion image of CT angiography and color-coded iodine map showing organized thrombi in both main pulmonary arteries (arrows) with a wedge-shaped perfusion defect in the right upper lobe. **C.** On the delayed-phase image, the area with a previous perfusion defect in the right upper lobe is enhanced due to the systemic collateral supply in chronic pulmonary thromboembolism.

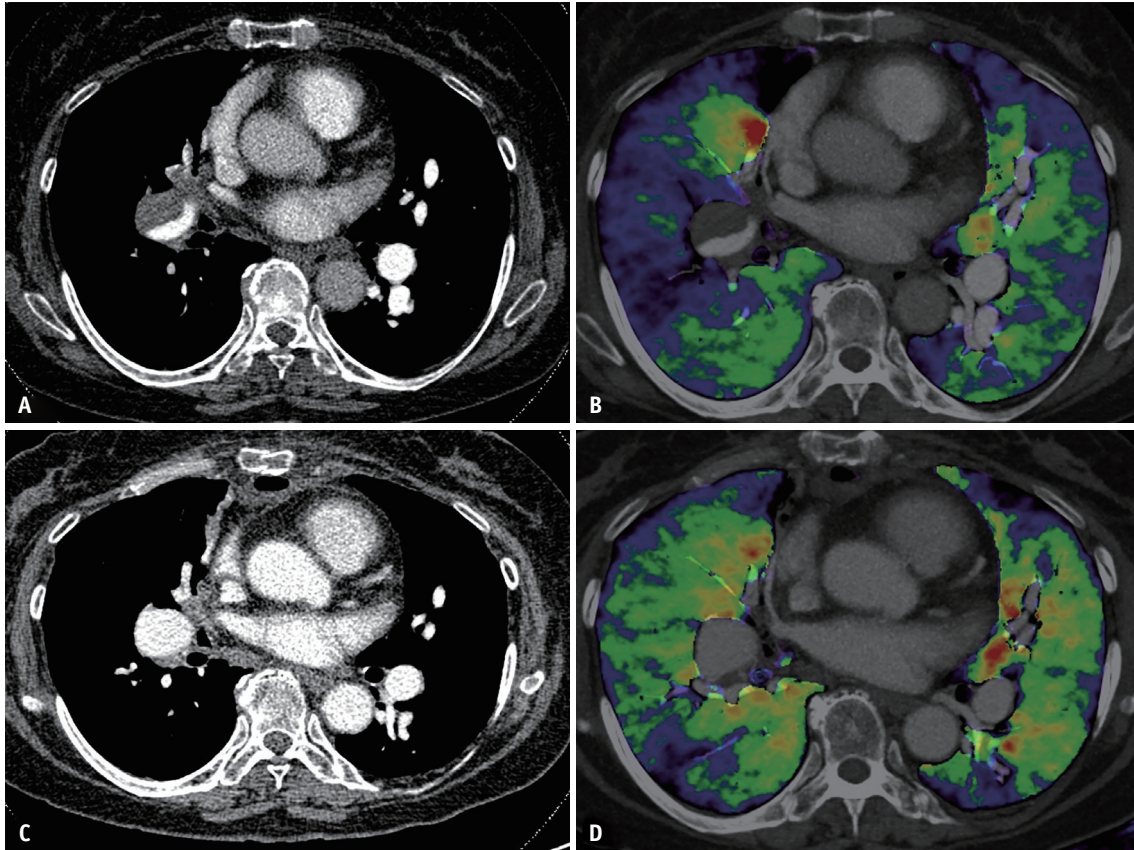
(CTEPH) develops in 2–4% of patients with acute PE [63–68]. Thromboembolic materials in the pulmonary vascular bed trigger vasoconstriction and remodeling [63,69], and progressive pulmonary hypertension and right heart failure can occur [69]. The prognosis of CTEPH is poor. Therefore, accurate diagnosis and prompt treatment are important for a better prognosis [63,68]. DECT can play a potential role in the diagnosis and treatment of CTEPH. It is useful for evaluating perfusion patterns and differentiating between CTEPH and PA hypertension. The authors found that 96.6% of segments from 19 patients with PA hypertension showed patchy perfusion defects (heterogeneous perfusion defects with intervening areas of preserved perfusion), while 12 patients with CTEPH usually showed patchy (58.5% of segments) or embolic-type (37.5% of segments) perfusion defects (wedge-shaped, pleural perfusion defects in the affected segment) on the iodine maps of DECT [70]. DECT is also useful for the severity assessment of CTEPH and evaluation of the treatment response in CTEPH (Fig. 6). Severity assessment and treatment are crucial for CTEPH because untreated CTEPH leads to a poorer prognosis compared to acute PE. A previous study reported that PBV scores obtained using DECT significantly correlated with PA pressure and pulmonary vascular resistance, and lung PBV scores are useful noninvasive estimators of CTEPH [71]. DECT can be used to measure an increase in lung perfusion following balloon pulmonary angioplasty (BAP) in patients with CTEPH [71]. The authors examined the clinical significance of PBV using DECT in eight patients with CTEPH undergoing BPA. They found increases in lung PBV values in the BPA-treated area and significant positive correlations

with improvement in whole-lung PBV. This study suggests that DECT may be a useful noninvasive tool for assessing the treatment outcome of BAP.

### Technical Consideration and Radiation Dose in DECT

In terms of radiation dose, initial studies reported that DECT was associated with higher radiation exposure than single-energy CT [72]. However, many studies have reported that DECT does not require the additional dose required for conventional CT [16,40,73]. A previous phantom study reported that the radiation doses of DECT pulmonary angiography were 2.61 mSV and 2.69 mSV for 140/80 kVp and Sn 140/100 kVp, respectively, which were similar to the 2.70-mSV dose for the standard 120-kVp protocol chest CT [73]. A two-phase imaging method may increase radiation dose. However, dose-reduction techniques, such as selective photon-shield usage and tube-current modulation, would be useful for minimizing the increase in radiation dose [61,74]. With the development of third-generation DECT, new levels of dual-energy voltage combination and thicker thin filters with a more precise spectral separation of X-rays allow lower radiation exposure with preserved image quality for CTPA examination than that with second-generation DECT or single-energy CT [75–77].

As mentioned above, many studies have used the perfusion defect size on DECT as a surrogate marker that represents disease severity or prognosis. However, the size of the perfusion defect varies depending on various factors (e.g., amount, concentration, injection rate of contrast



**Fig. 6. A 74-year-old female with chronic pulmonary embolism.**

**A.** CT angiography showing an eccentric chronic thrombus in the right lower pulmonary artery. **B.** The fusion image of CT angiography and color-coded iodine map showing a large eccentric chronic thrombus in the dilated right lower lobar pulmonary and multifocal perfusion defects in both lungs. **C, D.** After pulmonary endarterectomy, the organized thrombus was removed. The follow-up CT angiography image showing the contrast-enhanced right lower pulmonary artery after removal of the organized thrombus. An iodine map image demonstrates improved pulmonary perfusion on both lungs.

media, tube voltage, scan delay time, and machine). In addition, quantitative measurements are another major issue in DECT imaging because there are no standardized analytical methods or parameters in DECT. Therefore, several values need to be validated for applications, and some values are difficult to analyze.

As such, a scanning protocol should be considered. Currently, there is no standardized scanning protocol for evaluating perfusion defects on DECT. Several studies have proposed an image acquisition and contrast injection protocol to evaluate pulmonary disease using DECT [21,78]. Usually, an 80-kVp image is recommended for the lower tube voltage to better demonstrate small endoluminal clots [21,78]. To use contrast agents, a high-concentration iodine-based contrast material (> 300 mg/mL) is recommended to differentiate iodine from other materials. To inject the contrast media, the region of interest is usually placed in the main PA, and the bolus tracking

method is used. To evaluate the PA and lung parenchyma in a single scan, the delayed scan time should be longer (4–7 seconds). The scan direction should be caudocranial to avoid streaky artifacts caused by high-concentration contrast agents in the superior vena cava or upper thoracic veins. The use of saline chasers helps reduce artifacts and improve image quality. If chronic PE is suspected, a delayed-phase scan can be added to evaluate the perfusion pattern, but there is a concern regarding additional radiation exposure.

To achieve optimal parenchymal enhancement, the iodine injection technique, delay time for image acquisition, direction of CT data acquisition, and reduction of artifacts should be considered. We recommend the use of high-concentration iodine-based contrast agents, prolonged delayed scan time, caudocranial scanning direction, and single-phase scanning.



## Diagnostic Pitfalls of DECT

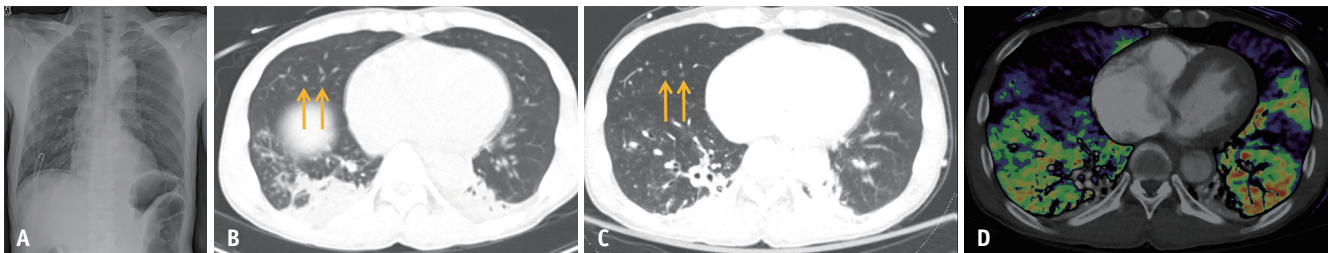
Familiarizing clinicians with diagnostic pitfalls of DECT perfusion imaging is important to avoid misdiagnosis. An iodine map of the lung parenchyma allows for the fast detection of perfusion defects and has high inter-reader agreement (Fig. 7). However, an iodine map must be interpreted with caution because iodine maps selectively demonstrate iodinated contrast material within the lung parenchyma, not true perfusion [32]. In addition, PE does not always cause perfusion defects in an iodine map [20,25,34,79]. Although the rate of perfusion defects on PBV for occlusive PE is relatively high (82–95%), the rate of perfusion of non-occlusive PE defects may be as low as 6–9% [20,25,34], and other lung diseases can also cause perfusion defects [80].

Streaky and beam-hardening effects around the rib,

metallic materials, and around the high-concentration contrast agent in vessels cause false perfusion defects in an iodine map. The thoracic vein, superior vena cava, and right cardiac chambers are common locations for heterogeneous artifacts in blood flow images. The right middle lobe and left lingular segment, which abut the cardiac border, also cause heterogeneous artifacts due to cardiac motion (Fig. 8). These should not be mistaken for true lesions.

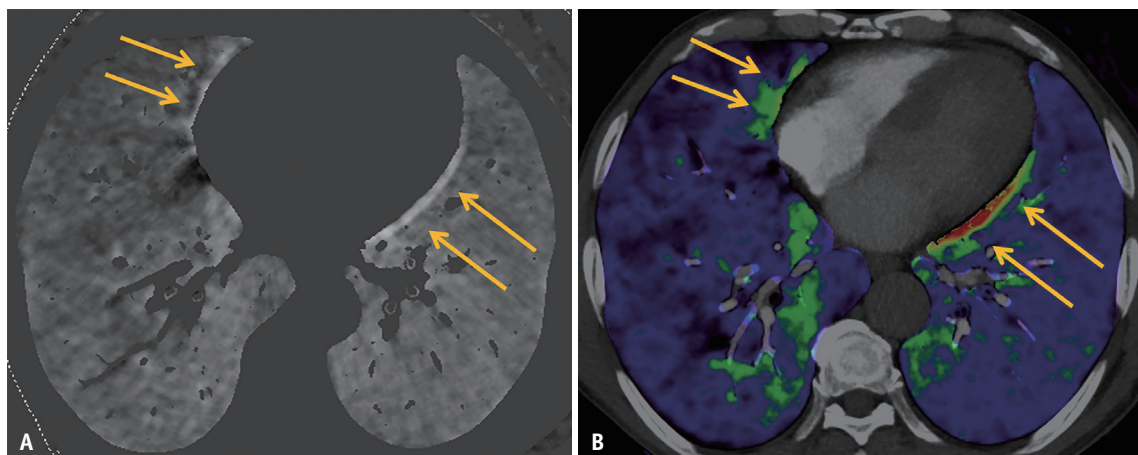
## Future Directions for Diagnosis of PE with DECT Using Artificial Intelligence

Artificial intelligence (AI) has received considerable attention in the field of radiology [81]. AI can also be used to diagnose PE [82]. In the early research of Blackmon et al. [83], they developed a computer-aided detection algorithm for PE using machine learning; this algorithm



**Fig. 7.** A 50-year-old male suddenly complained of dyspnea after removal of a central venous catheter on day 5 after distal pancreatectomy and splenectomy.

**A.** Chest X-ray on day 4 after the operation showing the normal position of the central venous catheter through the right internal jugular vein. **B, C.** Abdominal CT on day 4 after the operation showing dependent atelectasis without embolic lesions (**B**). Chest CT image after dyspnea is presented (**C**). Multifocal air is suspected in the right middle pulmonary arteries (arrows in **C**), which was not noted in the previous abdominal CT (arrows in **B**), and hypoattenuations in both anterior lungs can be seen. **D.** The fusion image of CT angiography and a color-coded iodine map showing large perfusion defects in the anterior portion of both lungs, which could have been caused by pulmonary air embolism. CT = computed tomography



**Fig. 8.** A 73-year-old male diagnosed with chronic pulmonary thromboembolism.

**A, B.** A gray scale (**A**) and a fusion image iodine map (**B**) shows that the right middle lobe and left lingular segment (arrows) which abut the cardiac border also cause heterogeneous artifacts due to cardiac motion.

improved the sensitivity of PE detection for inexperienced readers. In a recent study, Liu et al. [84] adapted deep-learning algorithms to detect and calculate the clot burden of acute PE using MDCT. They showed that deep-learning algorithms could detect acute PE with good performance and efficiently calculate the clot burden to reduce clinicians' workload. AI is useful for difficult tasks, such as the detection of small peripheral clots or automatic quantification of clot burden and RV/LV diameter ratio, which have been shown to be prognostic factors for acute PE. There are few studies on the application of AI in DECT imaging for PE. A recent study reported that deep learning-based automatic lung lobe segmentation and quantitative lobar or zonal perfusion analyses are useful in PE detection, although the study had a small sample size of only 88 patients [84]. Further large-scale studies applying AI to DECT images of PE are worthwhile. AI will serve to detect and characterize the emboli and predict patient prognosis by deep learning-based quantification of defect volume using DECT as a complementary diagnostic tool

## CONCLUSION

DECT is useful for detecting PE, assessing the severity of PE, and predicting prognosis. The technical and diagnostic pitfalls of DECT have been overcome with the standardization of protocols and advancements in CT technology. According to current guidelines, DECT is not regarded as a routine diagnostic procedure in the evaluation of PE. However, DECT has been recommended as an alternative tool for V/Q scanning in patients suspected of having CTEPH if appropriate expertise and resources are available on-site [7].

By adjusting image acquisition and post-processing methods based on clinical experience, the application of the dual-energy technique for the evaluation of PE could be expanded.

## Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

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## Author Contributions

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