Acute pulmonary embolism multimodality imaging prior to endovascular therapy

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Abstract
The manuscript discusses the application of CT pulmonary angiography, ventilation–perfusion scan, and magnetic resonance angiography to detect acute pulmonary embolism and to plan endovascular therapy. CT pulmonary angiography offers high accuracy, speed of acquisition, and widespread availability when applied to acute pulmonary embolism detection. This imaging modality also aids the planning of endovascular therapy by visualizing the number and distribution of emboli, determining ideal intra-procedural catheter position for treatment, and signs of right heart strain. Ventilation–perfusion scan and magnetic resonance angiography with and without contrast enhancement can also aid in the detection and pre-procedural planning of endovascular therapy in patients who are not candidates for CT pulmonary angiography.

Keywords
Acute pulmonary embolism · Computed tomography pulmonary angiography · Ventilation–perfusion scan · Magnetic resonance angiography

Introduction

Acute pulmonary embolism (PE) is a frequently encountered disease associated with high morbidity and mortality [1]. Most cases of acute PE originate from lower extremity deep vein thrombosis [2]. The thirty-day mortality rate is estimated to be 4%, and the one-year mortality rate is estimated to be 13% [3]. The incidence of acute PE is higher in males (56 per 100,000 people) compared to females (48 per 100,000 people) [4–6]. Advanced age is correlated with increased incidence of acute PE [5, 7].

Clinical evaluation of suspected acute PE

Acute PE presents with variable severity [8–11]. This can be explained by the varying degrees of pulmonary vasculature obstruction secondary to venous thromboembolism. Gradual increases in pulmonary artery pressure can be seen when greater than 30–50% of an arterial bed’s cross-sectional area is occluded as a result of stressed endothelial cells releasing thromboxane and other vasoactive mediators [12]. Increased pulmonary artery pressure resulting from acute PE obstruction increases right heart strain secondary to elevated right ventricular afterload [13]. Right ventricular dysfunction can be observed acutely as a result of the increased afterload as well as myocardial ischemia [2]. Continued stress on the ventricles can cause protracted contractions, ischemia, and desynchronization of the left and right ventricles [14]. Prolonged elevation of pulmonary vascular pressures can also cause pulmonary hypertension that lasts beyond the original event [15]. Dyspnea, pleuritic chest pain, and cough are the most common presenting symptoms of acute PE, while other signs of acute PE include unilateral leg edema, sinus tachycardia, and tachypnea [16, 17].

Initial testing for patients with suspected acute PE should include brain natriuretic peptide, troponin, and ECG (Table 1). These investigations can be helpful in narrowing
down the differential diagnosis. These tests also provide prognostic data when acute PE is present [9, 10, 18–29].

The Wells score is used to determine the pre-test probability of acute PE in hemodynamically stable patients. A patient's Wells score categorizes them as having a low, intermediate, or high pre-test probability of acute PE [1, 2, 32, 33]. The low, intermediate, and high risk categories correspond to 5.7%, 23.2%, and 49.3% pre-test probability of acute PE, respectively based on a 2010 meta-analysis [34]. A Wells score of zero essentially excludes the possibility of acute PE with a low false-negative rate and a high sensitivity. The modified Geneva score may also be used to determine the pre-test probability of acute PE. This scoring system utilizes clinical variables to categorize a patient into low, intermediate, or high risk groups that corresponded to 8%, 28%, and 74% prevalence of acute PE in one study [35]. A simplified version of the modified Geneva score has been found to maintain diagnostic accuracy and has been externally validated [36, 37].

Patients who are categorized as having a low or intermediate pre-test probability of acute PE can be assessed with a laboratory D-dimer test. A negative D-dimer test result in these patients essentially excludes the possibility of acute PE. A meta-analysis found that patients with a negative D-dimer and without a high pre-test probability of acute PE had a 0.14% 3-month incidence of venous thromboembolism [38]. It is important to consider that the D-dimer can also be nonspecifically elevated in certain conditions, such as pregnancy, recent hospitalization, active neoplastic disease, and other chronic inflammatory states. A prospective longitudinal study of 100 patients with systemic lupus erythematosus with recurrent activity found that unexplained, persistent elevation of D-dimer levels, especially above 2.0 µg/mL, were associated with elevated risk of thrombosis [39]. Another study found that D-dimer levels in patients with estimated glomerular filtration rate of 30–60 mL/min were 100% sensitive in ruling out acute PE although they were not specific enough to diagnose acute PE in this population [40]. Increased age has been associated with elevations in D-dimer concentrations, and a greater age-adjusted D-dimer threshold was found to be more specific (64% versus 54%) although less sensitive (93% versus 98%) in detecting acute PE in patients greater than 50 years old [41].

Patients with a high pre-test probability and occasionally those with intermediate pre-test probability require imaging to assess for acute PE. Computed tomography pulmonary angiography (CTPA) is usually the non-invasive imaging modality of choice. CTPA offers 83% sensitivity, 96% specificity, and 96% positive predictive value when diagnosing acute PE in patients considered to have a high pre-test probability [42]. A positive D-dimer test result also requires CTPA imaging to confirm or exclude acute PE [2, 32, 43]. The simplified Pulmonary Embolism Severity Index (sPESI) is a sensitive clinical prediction score used to risk stratify diagnosed acute PE patients [2, 44, 45]. This tool considers the variables of age > 80 years old, history of cancer, chronic cardiopulmonary disease, heart rate ≥ 110 beats per minute, systolic blood pressure < 100 mmHg, and arterial oxyhemoglobin saturation < 90%. A patient is scored by receiving one point per variable present [46]. A score of 0 is considered low-risk with an associated 1.0–1.5% 30-day mortality rate while a score of ≥ 1 is considered high-risk with a 10.7–10.9% 30-day mortality rate [46, 47]. Stratifying diagnosed acute PE patients by prognostic risk can be helpful in identifying low-risk patients who may benefit from outpatient therapy and revealing higher risk patients who should receive inpatient treatment [48]. The 2019 European Society of Cardiology PE guidelines utilize the sPESI in addition to right ventricular strain on echocardiogram or CT, elevated troponin levels, and hemodynamic instability to classify patients with PE as low-, intermediate-low, intermediate-high, and high-risk PE [49]. Other prognostic scoring systems including the Bova and FAST scores utilize clinical, imaging, and laboratory data to estimate risk of early PE-associated mortality although their implications for clinical decision-making have not yet been elucidated [50–55].

### Endovascular treatment of acute PE

The performance of endovascular therapy for acute PE treatment is evolving and gaining increasing interest. Endovascular treatment enables the removal of thromboembolic material from the pulmonary arterial system through

| Test                     | Value                                                                                                                                 |
|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Brain natriuretic peptide | Elevated levels associated with short-term mortality in hemodynamically stable patients with acute PE [22, 23]                      |
| Troponin                 | Elevated levels associated with greater in-hospital and short-term mortality in patients with acute PE [30, 31]                      |
| Electrocardiogram        | Abnormalities associated with acute PE (nonspecific) [9, 24] and greater risk of death in patients with acute PE [25, 28]               |
catheter-directed lysis or aspiration thrombectomy. Endo-
vascular treatment can be especially beneficial in patients
with persistent hypotension or shock secondary to acute
PE [56]. This treatment has the potential to improve right
ventricular function by relieving elevated pulmonary vas-
cular pressures and stabilizing hemodynamics [33].

A pulmonary embolism response team can help decide
on the best therapy for a patient with acute PE [57–59].
Endovascular therapy can be considered in patients with
contraindications to systemic thrombolysis who have
submassive acute PE, evidenced by elevated troponin and
brain natriuretic peptide, and right heart strain [33, 60,
61]. Endovascular therapy of acute PE usually involves
placing a side hole infusion catheter through the throm-
boembolism and infusing tissue plasminogen activator
(tPA). One mg of recombinant tPA per hour per catheter
for a maximum total of 24 mg is a typical dosage per the
SEATTLE protocol [62]. The ULTIMA trial found that
10–20 mg of recombinant tPA over 15 h in addition to
unfractionated heparin reversed right ventricular dilata-
tion at 24 h greater than unfractionated heparin alone
[63]. These doses are lower than that used in systemic
thrombolysis and are therefore thought to be associated
with a lower risk of intracranial or other hemorrhage [33].
Aspiration thrombectomy with immediate removal of the
offending thromboembolic material from the pulmonary
arterial system is another endovascular treatment approach
[33]. Aspiration thrombectomy is specifically beneficial
for patients with contraindication to systemic or catheter
directed thrombolysis secondary to bleeding risk
[64, 65].

The PERFECT registry prospectively enrolled 101
patients receiving catheter-directed therapy for acute PE
in a multicenter registry. The study showed that catheter-
directed therapy for acute PE decreased right-sided heart
strain and pulmonary artery pressures without causing
major bleeding events [66].

The OPTALYSE PE trial was a prospective, multi-
center, parallel-group trial that included 101 patients with
acute PE treated with ultrasound-assisted catheter-directed
thrombolysis. The patients were randomized to 4 groups
that varied by tPA dose (range of 4 to 12 mg) and infu-
sion duration (range of 2 to 6 h). The endpoints of RV/LV
diameter ratio and thromboembolic burden were sig-
nificantly decreased in the treatment groups. Major bleed-
ing occurred in only 4% of patients, and one intracranial
hemorrhage event was attributed to ultrasound-assisted
catheter-directed thrombolysis [67].

Studies have confirmed that endovascular treatment of
acute PE is safe and effective with regard to short term
hemodynamic stabilization. Additional studies should be
done to assess the effect of catheter-directed therapy on
long-term sequela of PE namely CTED and CTEPH with
right ventricular failure.

**CT pulmonary angiography for pre-procedural planning**

Computed tomography pulmonary angiography (CTPA)
is the current non-invasive imaging modality of choice to
assess acute PE. Its strengths include its accuracy, speed of
acquiring images, and widespread availability. CTPA may
reveal alternative diagnoses contributing to a patient’s pres-
entation if acute PE is not visualized [68]. A prospective
randomized trial assessing acute PE detection with CTPA
compared to pulmonary angiography as gold standard found
CTPA to have 91% accuracy [69]. CTPA also offers supe-
rior spatial resolution and multi-planar reconstruction [68].
Wide-array CT scanners can cover substantial length per
rotation and are associated with reduced motion artifacts.
Dual-energy CT can help to rule out acute segmental and
sub-segmental PE by color-coding perfusion based on the
iodine concentration (iodine or Z-effective mapping) [70].

Dual-energy CTPA involves using two distinct energy
levels to capture the image [71]. This technique enables dif-
ferratentiation between tissues with similar attenuation values
using various processing techniques such as iodine maps,
virtual non-contrast (VNC) and virtual monochromatic
images (VMI). Iodine maps accentuate iodine-containing
tissue and improve the sensitivity of perfusion defects. VNC
images imitate non-contrast images by virtually removing
iodine and can be used for calcium scoring or as a substitute
for true non-contrast images. VMI imitate an X-ray beam
with one energy level and are created by a linear combi-
nation of basis pair images in different proportions. VMI
can decrease artifacts and thereby improve specificity [71,
72]. Lung perfusion maps can be derived from iodine maps
(Figs. 1 and 2) [33]. A pulmonary perfused blood volume
(PBV) map color codes parenchymal tissue by iodine con-
centration [73, 74]. Perfusion defects are normalized to the
vascular iodine concentration, and areas that do not fall
within this attenuation range are excluded. Hence, lung
abnormalities appear dark on PBV maps. PBV maps can also
be merged with conventional CT images to better analyze
the lungs’ form and function [75, 76].

Dual-energy CT can salvage suboptimal studies and
reduce the contrast exposure to patients. This is accom-
plished by using low-energy VMI less than 70 keV, which
exhibits greater photoelectron attenuation and thus greater
contrast [77]. As many as 10% of regularly acquired CTPA
studies are non-diagnostic, and 40% of those are caused by
poor contrast enhancement [78]. While poorly enhanced
studies often require repeat contrast doses and repeat scan-
ning with associated radiation exposure, low energy VMI

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avoids this by virtually increasing vessel attenuation and contrast-to-noise ratio (CNR). The subjective image quality was found to be best at 70 keV VMI when compared to polyenergetic images in one study [79]. Another study found that 60 keV produced the greatest CNR and sound-to-noise ratio (SNR) while maintaining image quality and using 35% of the typical iodine concentration [80]. Dual-energy CT has also been found to produce high SNR, and CNR while requiring only 40% of the typical iodine based contrast agent dose [81].

High-energy VMI has the ability to reduce artifacts, with 100 keV producing the least artifacts [80]. Beam hardening artifacts originating from dense contrast in the superior vena cava is especially reduced with high-energy VMI [71]. The high-pitch helical mode of dual-source scanners also results in diagnostic image quality by requiring decreased breath hold duration and thus leading to reduced motion artifacts. This mode is also associated with decreased radiation and contrast exposure to the patient [82]. A retrospective study of ultra-high-pitch dual-source CTPA in patients with suspected PE found that a reduced voltage (100 kV) compared to a standard voltage (120 kV) resulted in significantly reduced radiation dose, greater subjective image quality, and improved SNR and CNR. Diagnostic agreement between readers for the reduced voltage was very high (κ = 0.891) [83]. Iterative reconstructive algorithms can further reduce patients’ radiation exposure [84]. A retrospective study of 4011 patients divided into three groups differentiated by CT optimization technique found that iterative reconstruction resulted in a significant radiation dose reduction of 16–31% when combined with automated tube current modulation. The same study found that iterative reconstruction improved levels of objective noise [85]. Another study found that iterative model reconstruction could reduce radiation doses up to 50% while preserving image quality [86].

CTPA can be helpful in the planning stages of endovascular therapy for acute PE. In the coronal orientation, it can reveal both the number and distribution of emboli. During

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Fig. 1 80-year-old female with known ANCA-negative, medium-size-vessel vasculitis presenting with progressive dyspnea over a period of 4 weeks. a Dual-energy CTPA demonstrates filling defects of several subsegmental arteries, one of them illustrated in this axial plane (arrow). b Z-effective map of the dual-energy CTPA demonstrating iodine distribution with blue colors representing high iodine concentration and yellow and red colors representing low iodine concentration. This axial plane at the same level shows a wedge-shaped area of low iodine concentration (arrows) corresponding to an area of reduced perfusion caused by the embolus seen in a. Further perfusion defects can be appreciated on the same plane (arrowheads) corresponding to more emboli not detected with regular CTPA imaging.

Fig. 2 64-year-old male with hepatocellular carcinoma. a Dual-energy CTPA demonstrates filling defects of several subsegmental arteries, one of them illustrated in this axial plane (arrow). b Z-effective map of the dual-energy CTPA illustrates a wedge-shaped area of low iodine concentration at the same level corresponding to an area of reduced perfusion (arrow).
the procedure coronal reconstruction can be correlated to CTPA images to ensure proper catheter position within the acute thromboembolic material. Right heart strain is a common pathology associated with acute PE, and CTPA reveals signs of right heart strain including increased RV/LV diameter ratio of 0.9 or greater, interventricular septal bowing towards the left ventricle, contrast reflux into the hepatic vein as well as inferior vena cava (IVC), and increased IVC diameter compared to baseline [87]. Capturing the pulmonary artery size allows its comparison to prior CTs and may show an acute enlargement secondary to PE. CTPA also enables characterization of the venous anatomy including proximal IVC and the patency of the central veins.

This information is important for access planning purposes (Figs. 3 and 4).

Dual-energy CT perfusion images simulate true perfusion by allowing the comparison of a tissue’s innate physical density with its enhancement during acquisition [88]. These perfusion images do not require changing the CTA protocol, which confers the benefits of not requiring additional radiation or contrast and thereby minimizing motion misregistration from repeated acquisitions [88]. The resulting images correlate well with those of scintigraphic perfusion images. PBV images have shown modest correlation with lung scintigraphy in CTEPH patients [89]. One study of dual-energy CT perfusion images compared to scintigraphy showed 96% sensitivity and 76% specificity [90]. Another
A study comparing dual-energy CT perfusion images to scintigraphy at the segmental level showed 83% sensitivity and 99% specificity [91].

Acute and chronic PE present differently on CTPA. Acute PEs are typically located at vessel bifurcations and may completely or partially obstruct pulmonary vasculature [13, 32]. A complete obstruction is characterized on CTPA as a hypoattenuating contrast defect occupying a vessel’s entire lumen and can be seen in acute PE. The vessel diameter at the obstruction level is usually maintained or increased slightly. Partial obstructions may be located centrally (indicative of acute PE) or eccentrically (indicative of chronic PE). Complete obstruction in the setting of acute PE can cause distal infarcts that appear on CTPA as a triangular subpleural consolidation or ground-glass opacity with fine reticular changes.

Chronic PE appearance varies based on the extent of obstruction and degree of chronicity. Complete obstruction presents as a lack of contrast distal to the obstruction and an immediate narrowing of the vessel diameter. Partial obstruction is characterized by a narrow diameter and partially attenuated vessel or dilation distal to the obstruction. Chronic nonobstructive PE manifests as a narrow vessel, irregular intima, and intraluminal bands and webs [13]. The abrupt narrowing of vessels is caused by recanalization of the thrombus. Thrombi along a vessel wall can become endothelialized or “laminated” and will appear as an irregular intimal surface contour that forms obtuse angles with the contrast column. Laminated thrombi often present with calcifications. Bands are linear structures that run along the long axis of a vessel and may appear in the setting of chronic PE. Webs are networks of bands that are often found at vessel bifurcations in chronic PE and are associated with distal neovascularature [13, 92, 93].

Chronic PE raises vascular resistance and is characterized by dilation of the central pulmonary arteries secondary to pulmonary hypertension. The main pulmonary artery (MPA) diameter at the level of its bifurcation lateral to the ascending aorta is used to assess for the presence of pulmonary hypertension. MPA diameters greater than 28 mm in men and 27 mm in women are typical predictive cut-offs for pulmonary hypertension [94]. A greater cut-off of 31.6 mm has also been suggested [95]. A MPA-to-ascending aorta diameter ratio greater than 1 is also a reliable method of assessing for pulmonary hypertension. This measurement offers 70% sensitivity, 92% specificity, 96% positive predictive value, and 52% negative predictive value [96]. In CTEPH pulmonary arteries can appear tortuous with calcified walls [13].

Chronic PE can present with right ventricular hypertrophy evidenced by ventricular wall thickness greater than 4 mm [13]. Development of right ventricular dysfunction causes right ventricular enlargement [87]. Right ventricular enlargement can dilate the tricuspid valve annulus leading to tricuspid regurgitation. The lung parenchyma distal to the occlusion or stenosis of chronic PE presents with a mosaic perfusion pattern that appears as well-demarcated hypoattenuated tissue with narrow vasculature contrasted with the hyperattenuated tissue being in possession of larger vasculature of well-perfused lung parenchyma. Areas of infarction can resolve in the long-term to form peripheral nodules, cavities, subpleural scars, or irregular peripheral lines [13].

Right heart strain is important to recognize on CTPA and has characteristic signs on imaging as previously described (Fig. 5). A RV/LV diameter ratio ≥ 0.9 is predictive for poor clinical outcomes after acute PE [43, 97, 98]. A study of 457
patients found that RV/LV diameter ratio ≥ 0.9 was an accurate predictor of in-hospital death or clinical deterioration [87]. A meta-analysis found that right ventricular dilation is associated with elevated 30-day mortality, increased risk of death from PE, and increased 3-month mortality rate (OR 4.65) [99].

Ten to fifteen percent of acute PEs cause infarction of the lung. This appears as a wedge-shaped peripheral lung opacity, often referred to as a “Hampton hump,” on CTPA. These opacities can have a central ground glass appearance [33].

CTPA has its inherent limitations secondary to artifacts. Patient breathing causes motion artifacts that particularly affect the lower lung zones. Cardiac motion may also disrupt the pericardial zone image quality. Attenuation along a vessel may be disturbed by beam hardening artifacts from contrast originating from abutting vasculature, wires, or medical devices [33]. Studies have found 0.5% to 12.1% of CTPA studies to be non-diagnostic [78, 100–112].

**Ventilation/perfusion scan**

Ventilation/Perfusion (V/Q) scanning was the mainstay diagnostic method for acute PE before the development of newer CT techniques [113]. This imaging modality can be valuable when estimating the probability of an acute PE [114, 115]. Patients who are pregnant, have renal failure or contrast allergies, or cannot fit into a CT scanner also particularly benefit from V/Q scans. V/Q scans expose patients’ breasts to 50 times less radiation compared to CT, which helps to reduce breast cancer risk in young women [116–118]. The fetal radiation dose associated with V/Q scans has been estimated to be 3.4–6 times higher than the fetal radiation dose associated with low-dose CTPA. While V/Q scans are associated with a greater fetal risk for childhood cancer compared to CTPA, their aggregated radiation risk for a pregnant patient and her fetus is lower compared to CTPA. This difference in aggregated radiation risk increases with greater maternal body mass index and increased gestational age and suggests that V/Q scans are more dose-efficient than CTPA for pregnant patients [119, 120].

V/Q scan is the indicated diagnostic test for acute PE in pregnant patients with a normal chest radiograph. A retrospective study of 304 pregnant or postpartum women suspected to have an acute PE found that the patients with a normal chest radiograph were more likely to have a diagnostic image from V/Q scanning compared to CTPA. Various retrospective studies have found that 75–93% of V/Q scans of pregnant patients suspected to have acute PE resulted in diagnostic studies [11, 121–127]. CTPA has also been associated with a significantly higher incidence of sub-optimal studies for assessing acute PE in pregnant patients compared to age-matched non-pregnant controls [128]. This further contributes to the evidence supporting V/Q scan as the diagnostic test of choice in pregnant patients with a normal chest radiograph who are suspected to have acute PE.

V/Q scans make use of ventilation agents labeled with technetium-99 m (Tc-99 m) or radioactive noble gases such as Xenon-133 or Krypton-81 m. Technetium-99 m-labeled diethyleneetriaminepentaacetic acid (DTPA) is the most commonly used agent [115].

Tc-99 m-labeled macro-aggregated albumin (MAA) is injected intravenously to image perfusion for V/Q scans. The patient is positioned upright for the scan, which acquires multiple planar images. Single-photon emission computed tomography (SPECT)/CT using a low-dose CT technique may also be performed to better localize abnormalities [115].

The perfusion scan may be acquired before or after the ventilation scan. Imaging perfusion first guides the projection used for ventilation scans using Xenon-133. A normal perfusion scan can preclude the need for a ventilation scan, which is particularly valuable for patients requiring minimization of radiation exposure such as the pregnant patient population. Some authors have proposed primarily using perfusion-only scintigraphy in the diagnostic assessment of acute pulmonary embolism to reduce potential viral transmission by aerosolization in the setting of the current global COVID-19 pandemic [129].
V/Q scans are interpreted with a corresponding chest radiograph taken within 12–24 h of the scan. Acute PE is often visualized as peripheral wedge-shaped perfusion defects in a lobar, segmental, or sub-segmental distribution in the absence of an associated ventilation abnormality. This mismatched defect can also be found with other conditions including malignancy, vascular abnormalities, vasculitis, veno-occlusive disease, and mediastinal lymphadenopathy and therefore a chest radiograph is valuable for comparison purposes [43].

The most commonly used criteria for interpretation of V/Q scans for acute PE are the modified Prospective Investigation of Pulmonary Embolism Diagnosis (PIOPED) II and prospective investigative study of acute pulmonary embolism diagnosis (PISAPED) criteria [115, 130]. Patients can be categorized as high probability, intermediate probability, very low probability, normal, and non-diagnostic using the modified PIOPED II criteria. A normal scan is characterized by diffusely homogenous radiotracer activity in the lungs on ventilation and perfusion scans while a high probability scan is characterized by two or more large segmental mismatch defects or segmental defect equivalents. A very low probability scan will appear as a non-segmental defect [115].

The PIOPED II criteria have found V/Q scans to have 85% sensitivity and 93% specificity for acute PE, and the PISAPED criteria found to have 80% sensitivity and 97% specificity for diagnosing PE [113, 130]. Utilizing SPECT can improve V/Q scan sensitivity and specificity by enabling three-dimensional visualization of the lung. The addition of SPECT has been found to offer a 97% sensitivity and 91% specificity for diagnosing acute PE [131].

**Magnetic resonance angiography**

Magnetic resonance angiography (MRA) is an evolving imaging modality that can be used for evaluating the possibility of acute PE in certain patient populations. Pregnant or young patients may benefit from MRA instead of CTPA if acute PE is suspected due to the lack of ionizing radiation exposure. Patients with history of anaphylactoid reactions to iodine contrast media and those with chronic kidney disease may benefit from MRA as well [132].

MRA assessment for acute PE includes axial and coronal static steady-state free precession (SSFP) sequences, contrast-enhanced 3D MRA using T1-weighted GRE sequences, and an optional time-resolved contrast-enhanced 3D MRA for dynamic perfusion imaging [133].

The static SSFP sequences are acquired during free breathing or inspiratory breath-hold. These sequences can detect acute PE without the use of IV contrast due to the bright blood signal (Fig. 6). A non-contrast MRA is especially valuable for pregnant patients who ideally should not receive gadolinium contrast [33, 134]. The 3D-balanced

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**Fig. 6** 62-year-old female patient with acute dyspnea. a Static SSFP sequence acquired in coronal orientation shows a filling defect in the right upper lobe artery (white arrows). b and c Contrast-enhanced 3D MRA acquired in coronal orientation in the pulmonary arterial phase (b) and 25 s later (c) confirms the findings of the SSFP sequence (white arrows). d Time-resolved, contrast-enhanced 3D MRA demonstrates a corresponding perfusion defect in the right upper lobe (black arrows) as well as further perfusion defects in the right and left basal segments (black arrow heads, corresponding thromboemboli not illustrated in this figure)
SSFP sequence is commonly used. It creates T2/T1 weighting with radiofrequency pulse phase alteration and gradient echo refocusing that results in a steady state. A long T2 with high signal contrast causes blood to appear bright which facilitates thrombus detection [134]. This sequence offers high sensitivity for field heterogeneity and requires only a short repetition time to minimize artifacts [135]. Balanced SSFP has also been shown to provide fast, accurate measurement of pulmonary artery diameters [136]. Arterial spin labelling makes use of slice selective acquisition with repeat imaging after an initial inversion pulse. It can be particularly valuable when combined with faster sequences. This technique acquires an image with upstream blood tagged by an inversion radiofrequency pulse and another image without such tagging [134]. A subtraction between these images depict signal solely from the tagged blood and helps with visualizing vessels and tissue perfusion [137]. The fresh blood imaging technique makes use of the EKG-gated 3D partial Fourier fast spin echo technique. This sequence makes arterial blood in systole appear dark because of flow void and in diastole appear bright because of slows flow. Veins produce some intensity in systole and diastole due to slow flow [134]. An image with high signal intensity in the arteries and low signal intensity in the veins can be created by subtracting the systolic and diastolic images [137]. However this sequence is not commonly used to diagnose PE due to its susceptibility to misregistration [134].

Contrast-enhanced 3D MRA offers high spatial resolution of the pulmonary vasculature (Fig. 7). This technique utilizes intravenous gadolinium contrast that causes T1 shortening in adjacent tissues leading to a high signal intensity in MRA images [134]. Coronal images are typically acquired during inspiratory breath-holds. Usually pre-contrast images for subtraction purposes are obtained, followed by arterial phase images, and late arterial phase images [133]. Timing the acquisition accurately achieves high SNR and allows separation of the arterial and venous phase [134]. The time at which the pulmonary arteries achieve maximum contrast enhancement is assessed utilizing a bolus-tracking technique (Fig. 6) [33]. Bolus-tracking techniques include utilization of dynamic low resolution magnetic resonance fluoroscopy and starting the acquisition just before contrast enters the pulmonary arterial tree. One could also utilize a test bolus injection of 1 to 2 mL of contrast to assess the time required for the contrast to reach the target vasculature [134].

3D T1-weighted spoiled gradient echo sequence acquisition uses values of TR = 2.5–3 ms, TE = 1.0–1.5 ms, flip angle = 30–40°, matrix = 40 × 192 × 256, FOV = 460 mm, and parallel imaging factor (R) = 2 [138]. Acquiring data in an oval area of k-space and zero-filling corners enables isotropic spatial resolution. Fractional echo read-out can reduce TE and TR. This sequence can achieve 2 mm spatial resolution in phase encoded direction and 1.5 mm spatial resolution in frequency encoded direction [139]. Time-resolved contrast-enhanced 3D MRA is performed with repeated rapid volumetric sequences that sample the center of the k-space more frequently than the periphery [140, 141]. Data that are missing at each time point are shared between k-spaces by applying a variety of techniques [142–145]. The images are captured during shallow breathing after the first bolus injection.

**Fig. 7** 69-year-old male with acute dyspnea. a and b Contrast-enhanced 3D MRA acquired in coronal orientation demonstrates filling defects, among others a long filling defect in the left lower lobe artery with a “railway sign” (a, white arrows) and the filling defect is shown as a “polo mint sign” on the axial reconstruction of the same data set (b, white arrow). c Time-resolved, contrast-enhanced 3D MRA reveals extensive wedge-shaped perfusion defects in the left upper and lower lobes (black arrows).
pass of a gadolinium contrast bolus. There is some evidence that time-resolved contrast-enhanced MRA during patient free-breathing may achieve accurate diagnoses and vessel measurements, which could make this sequence especially beneficial in the pediatric population and in patients with severe dyspnea [146]. When using power injectors this technique is particularly helpful for visualizing perfusion defects when pursuing subtraction images (Fig. 6d and 7c) [147, 148].

**Conclusion**

Imaging plays a crucial role in the assessment of acute pulmonary embolism (PE) prior to endovascular intervention. CTPA is the modality of choice for the diagnosis of acute PE given its availability as well as excellent sensitivity and specificity. This imaging modality facilitates detection and characterization of the extent of the pulmonary embolus (particularly helpful in coronal view to correlate with angiography in the case of endovascular treatment) and enables assessment of right heart strain. Further, CTPA allows evaluation of the access route for endovascular interventions to ensure patency of the central venous system. MRI offers a limited role in the diagnosis of acute PE in certain patient populations, specifically in pregnant patients. In current clinical practice 3D MRA largely relies on Gadolinium based contrast administration for diagnosis of acute PE. However, non-contrast MRA sequences such as SSFP are evolving for the assessment of the pulmonary arterial vasculature.

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**Compliance with ethical standards**

**Conflict of interest** The authors declares that they have no conflict of interest.

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