IMPROVING PROTOCOLS

Computed tomography and magnetic resonance imaging for pulmonary embolus evaluation in children: up-to-date review on practical imaging protocols

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Abstract

Pulmonary embolism (PE) is a potentially life-threatening condition that requires immediate medical intervention. Although PE was previously thought to occur infrequently in the pediatric population, recent studies have found a higher-than-expected prevalence of PE in the pediatric population of up to 15.5%. The imaging modality of choice for detecting PE in the pediatric population is multi-detector CT angiography, although MRI is assuming a growing and more important role as a potential alternative modality. Given the recent advances in both computed tomography pulmonary angiography (CTPA) and MRI techniques, a growing population of pediatric patients with complex comorbidities (such as children with a history of surgeries for congenital heart disease repair), and the recent waves of coronavirus disease 2019 (COVID-19) and multisystem inflammatory syndrome in children (MIS-C), which are associated with increased risk of PE, there is new and increased need for an up-to-date review of practical CT and MRI protocols for PE evaluation in children. This article provides guidance for up-to-date CT and MR imaging techniques, reviews key recent studies on the imaging of pediatric PE, and discusses relevant pediatric PE imaging pearls and pitfalls, in hopes of providing readers with up-to-date and accurate practice for imaging evaluation of PE in children.

Keywords Children · Computed tomography · Lungs · Magnetic resonance angiography · Protocols · Pulmonary arteries · Pulmonary embolism

Introduction

Pulmonary embolism (PE) is an acute occlusion of the pulmonary arterial supply, usually by a thrombus. PE can be life-threatening without immediate and proper medical intervention and management. In the past, PE was thought to occur infrequently in the pediatric population. However, more recent studies demonstrated the prevalence of PE in the pediatric population to be substantially higher than originally thought, approaching the prevalence of PE in the adult population. For example, two seminal studies found a 14–16% prevalence of PE in pediatric patients who

underwent CT pulmonary angiography (CTPA) for workup of PE [1, 2]. The imaging modality of choice for detecting PE is CTPA using multi-detector CT, which can confirm the diagnosis of PE by noninvasively showing both direct (i.e. blood clot within the pulmonary artery) and indirect (i.e. lung parenchymal abnormality) signs of PE [3–5].

Although CTPA is highly sensitive and specific for detecting PE in both children and adults, the diagnostic accuracy depends substantially on the image quality. Therefore, the optimization of CTPA imaging protocols is particularly important, especially in the pediatric population. Furthermore, since the advent of the Delta and subsequent Omicron severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) variants in the last year, there has been increasing utilization of CTPA imaging for detecting pulmonary emboli in children. One reason for this increased use of CTPA in children is that high positivity rates of SARS-CoV-2 in the pediatric population have led to higher rates of multisystem inflammatory syndrome in children (MIS-C). Recent studies have suggested an increased incidence of PE of 25% in

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children with MIS-C who were evaluated with CTPA [6]. PE associated with MIS-C often involves the smaller pulmonary arteries (segmental and subsegmental), underscoring the importance of optimizing the image quality of pediatric CTPA studies to increase accurate diagnosis of PE in the pediatric population [6–8].

In addition, in recent years, MRI has assumed an important role as a potential alternative imaging modality for evaluating PE, mainly because it does not involve harmful ionizing radiation exposure (the major drawback of CTPA). However, there is a lack of awareness and standardization of MRI protocols for detecting PE, especially in the pediatric population. Therefore, the goal of this article was to provide an up-to-date review of practical CT and MRI protocols for PE evaluation in children.

Practical imaging protocols for pulmonary embolism in children

Computed tomography pulmonary angiography

The technical parameters of CTPA protocols, including patient preparation, contrast administration, CTPA parameters, scan timing and scan direction, require careful consideration for optimal image quality, especially in children.

Patient preparation

Sedation is typically no longer necessary for CTPA in children because of the increased numbers of detectors present in most modern multi-detector CT scanners, allowing the entire thorax to be scanned in less than a second. However, having CT technologists and staff trained in working with pediatric patients and coaching them prior to scanning are important aspects of patient preparation. This pre-imaging pediatric patient preparation can increase the child's cooperation and decrease motion artifact, resulting in best possible quality CTPA images. It is important to note that sedation might be required in some cases, such as in older children who are unable to follow directions or lie still on the scanner table, and during inspiratory–expiratory phase imaging in young children who are concurrently being assessed for interstitial lung disease.

Contrast administration

At the authors' institution, CTPA is performed with nonionic iodinated intravenous (IV) contrast agent administered at a dose of 1.5 mL/kg (maximum dose 150 mL). Contrast injection rates depend on both the site and the size of the peripheral IV catheter, although faster injection rates are preferred to optimize pulmonary arterial opacification. In general, for pediatric patients presenting with a secured antecubital intravenous catheter, injection rates are based on catheter size, with examples as follows: 2.5–4.0 mL/s in a 20-gauge (G) catheter (mechanical power injection), 1.5–2.5 mL/s in a 22-G catheter (mechanical injection) and 1.0 mL/s in a 24-G catheter (manual). Manual injection is typically required for small catheters inserted in the hand and foot, at an injection rate of 0.5–1.0 mL/s in infants and young children [2, 9]. A study comparing the difference between manual and mechanical injection of IV contrast agents on the diagnostic quality of pediatric CTPA showed that the degree of enhancement within the pulmonary arteries was not statistically different between the two IV contrast injection methods [10]. Therefore, it is possible to perform diagnostic-quality CTPA for the assessment of the pulmonary arteries with manual injection of IV contrast material in pediatric patients with small-gauge IV catheters [10]. As an alternative to manual injection, 24-G catheters allowing for infusion rates of up to 3 mL/s are available; however, their use depends on a balance of cost, staff preference and patient selection.

In the setting of a suboptimal or non-diagnostic study resulting from inadequate contrast opacification of the pulmonary arteries, one could consider: (1) an immediate follow-up MR angiography PE study, (2) a repeat CTPA study 24 h post contrast administration and checking the child's renal function or (3) a follow-up evaluation with nuclear medicine ventilation-perfusion study. Method of choice should be based on patient age and clinical status, scanner availability and the underlying reasons for the poor study. Ultimate decision-making should be based on discussions with the ordering provider.

Computed tomography pulmonary angiography parameters

At the authors' institution, low-dose multi-detector CT parameters are used to decrease radiation dose in pediatric patients, including weight- and age-based kilovoltage peak (kVp) as follows: 80 kVp (< 1 year), 100 kVp (1–4 years/40 kg) and 120 kVp (> 4 years). Our institution uses 150 mAs as reference for CTPA studies. Patient dosing is variable depending on patient size. In addition, automated exposure control systems modulate tube current along the x-, y- and z-axes. At our institution, a state-of-the-art dual-energy CT with 192 slices (Somatom Force; Siemens, Erlangen, Germany) is predominantly used for CTPA imaging. However, the following CT technical parameters (0.75-mm collimation for 16-multi-detector CT, 0.625-mm collimation for 32-multi-detector CT and 0.6-mm collimation for 64-multi-detector CT, with a pitch equivalent of 1.0–1.5) have been used for other multi-detector CT scanners.

Scan timing

The three main methods for intravenous contrast timing for CTPA studies are: (1) pre-scan test bolus, (2) fixed-time delay and (3) bolus tracking. In the pre-scan test bolus method, a small amount of intravenous contrast agent (~ 10 mL) deemed the "test bolus" is injected initially to detect the accurate time for intravenous contrast agent to reach the pulmonary artery and to calculate the most accurate delay time between the contrast injection and the initiation of scanning. Because the pre-scan test bolus method inherently increases radiation dosage, it is not often used in the pediatric population. The fixed-time delay method uses a set time delay after the end of contrast injection to scan initiation (typically 15–25 s). Because of the variation in pediatric heart rates and patient sizes, the fixed-time delay method often results in suboptimal contrast opacification of the pulmonary arteries and is not used for CTPA at our institution [11]. However, it is worth noting that up to 21% of respondents reported using fixed-time method for CTPA scan initiation in a multi-institutional survey conducted by Lee and colleagues [5]. At our institution, the bolus tracking method is preferred for intravenous contrast timing and CT scan initiation in the pediatric population. This technique is based on a region of interest (ROI) placed over the main pulmonary artery during contrast administration, followed by a series of low-dose images acquired at the ROI until the desired Hounsfield unit (HU) threshold of 150–200 HU is reached within the ROI.

Scan direction

For optimal CTPA technique, scanning is performed in a caudocranial direction to minimize respiratory motion artifact at the lung bases, where PEs have been demonstrated to occur at a higher frequency (in both pediatric patients and adults) compared with the upper lobes — 24–37% vs. 12–15% [2].

Special considerations (for the pediatric patients' status post congenital heart disease repair)

Advances in cardiac surgical technique and improved postoperative management have fortunately resulted in improved survival and longer life expectancy in children with congenital heart disease. Consequently, many pediatric patients with prior congenital heart disease repair now require CTPA for PE evaluation. These pediatric patients with a history of congenital heart disease can pose unique and substantial challenges for optimizing pulmonary arterial enhancement and obtaining diagnostic-quality CTPA imaging. Two main scenarios are children with prior Lecompte maneuver and prior Fontan procedure.

The Lecompte maneuver is a technique of the arterial switch operation for D-transposition of the great arteries first described by Yves Lecompte in 1981 [12]. During the Lecompte maneuver, the main pulmonary artery (MPA) is transected and the pulmonary artery bifurcation is brought anterior to the aorta followed by reconstruction of the right ventricular outflow tract (RVOT). It is important to recognize that the MPA lies anterior to the aorta after this surgical procedure so that the ROI of the monitoring slice can be placed in the correct vessel for optimum contrast opacification in the pulmonary arteries (Figs. 1 and 2).

Optimal pulmonary artery opacification is also challenging in pediatric patients who have undergone the Fontan procedure. Fontan patients undergo a multistage surgical
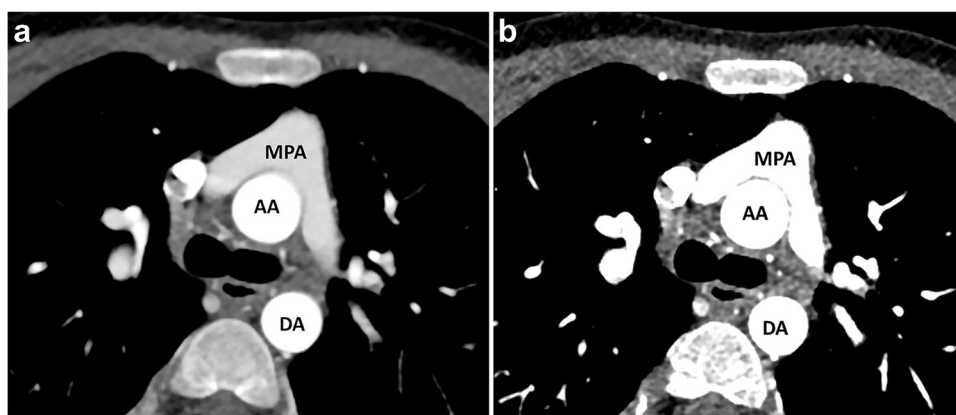

Fig. 1 Optimization of contrast opacification for computed tomography pulmonary angiography (CTPA) in an 11-year-old boy status post Lecompte maneuver for underlying D-transposition of the great arteries. **a** Axial enhanced CT image shows suboptimal opacification of the main pulmonary artery (*MPA*) for evaluation of pulmonary embolism because of inaccurate placement of the region of interest in the ascending aorta (*AA*) (instead of the MPA) for bolus tracking for CT scan timing. The MPA Hounsfield unit (HU) was 57. *DA* descending aorta. **b** Axial enhanced CT image demonstrates optimal opacification of the MPA for evaluation of pulmonary embolism. Attenuation of the MPA was 229 HU
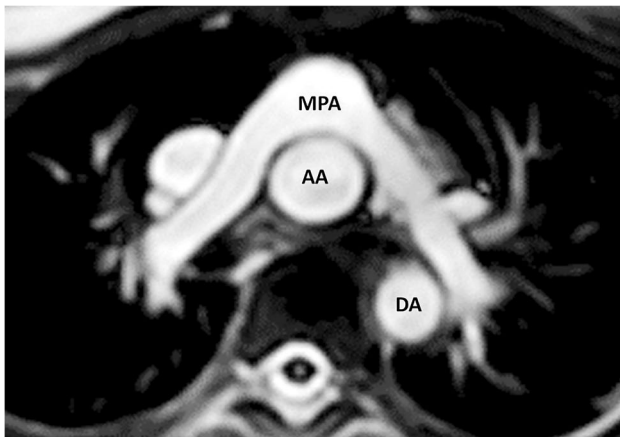
Fig. 2 Optimized visualization of the pulmonary artery on MRI in a 4-year-old boy status post Lecompte maneuver for underlying D-transposition of the great arteries. Axial white blood MRI sequence demonstrates homogeneous signal intensity throughout the well-visualized main pulmonary artery (*MPA*) draping over the ascending aorta (*AA*), the expected postsurgical finding in children after Lecompte maneuver. *DA* descending aorta

procedure to augment pulmonary arterial blood flow in the setting of single-ventricle physiology, which concludes with diversion of systemic venous blood return directly into the pulmonary arteries from the superior vena cava and inferior vena cava. Because of the absence of contrast agent mixing in the right atrium and ventricle, three practical methods can be used to optimize pulmonary arterial enhancement in Fontan patients: (1) simultaneous contrast administration through both the upper and lower extremities (2/3 contrast administered via the upper extremity and 1/3 contrast via the lower extremity), (2) use of bolus tracking within the Fontan pathway and the pulmonary arteries to initiate scan acquisition and (3) delayed second-phase CT (90-s delay)

(Fig. 3) [13]. At the authors' pediatric institution, there is anecdotal evidence of successful image acquisition with all three methods and the choice of imaging methodology is mainly based on the availability of upper- and lower-extremity catheters (or ease of catheter placement) in the child, the availability of nursing staff skilled in the placement of catheters in children with specific clinical needs, the availability of radiology technologists experienced with non-standard bolus tracking locations for pulmonary arterial imaging, the size and weight of the child, as well as patient heart rate and cardiac function.

Post-processing techniques

Multiplanar reconstruction

Multiplanar reformats (MPR) are reconstructions of raw axial multi-detector CT datasets into different planes relative to the x-, y- and z-axes with predefined slice thickness. MPR images are generated with slice thickness of 1.5 mm in the axial, coronal and sagittal planes as part of our standard protocol at the authors' institution. In addition to subjectively facilitating anatomical review, MPR imaging has been demonstrated to significantly increase reader confidence and interobserver agreement in the detection of PE in children, especially among trainees, compared with axial imaging alone, although interpretation time also increases [14].

Maximum-intensity projection reconstruction

Maximum-intensity projection (MIP) reconstructions are generated using a volume-rendering technique that projects the highest attenuating voxel on every plane of view within an algorithmically determined volume onto a two-dimensional (2-D) image. At the authors' institution, axial,
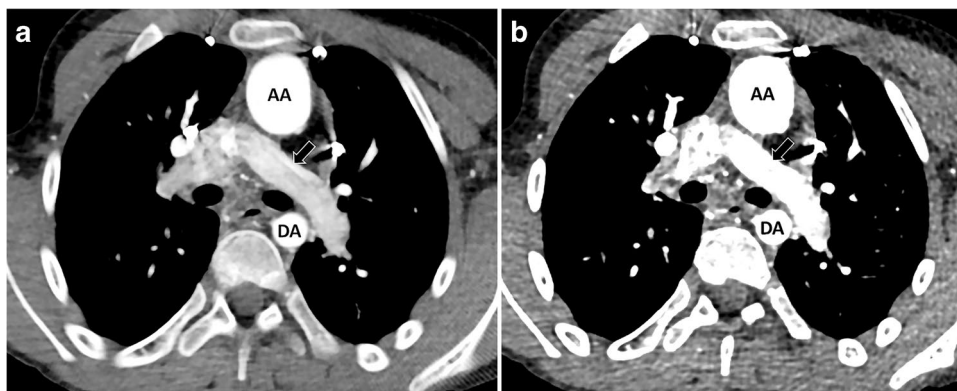

Fig. 3 Optimization of contrast opacification of computed tomography pulmonary angiography (CTPA) in a 10-year-old girl status post Fontan procedure for the single-ventricle physiology. **a** Axial enhanced CT image shows poor (incomplete) opacification of the pulmonary artery (*arrow*) rather than true pulmonary embolism. *AA* ascending aorta, *DA* descending aorta. **b** Axial enhanced CT image delayed 80 s demonstrates complete opacification of the pulmonary artery (*arrow*), confirming the absence of true pulmonary embolism
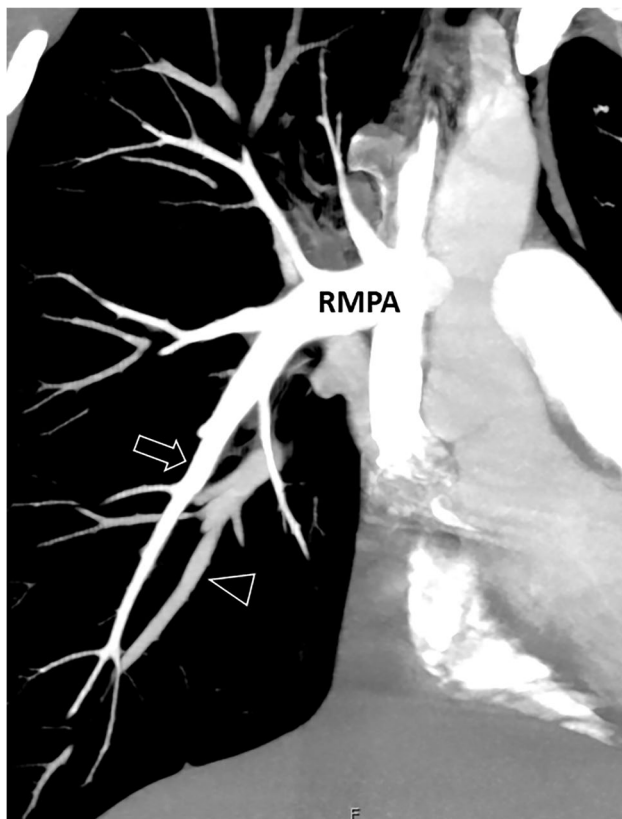
Fig. 4 Oblique maximum-intensity projection (MIP) CT image of right-side pulmonary artery in a 9-year-old girl. Oblique MIP CT image shows a well-opacified right lower lobe pulmonary artery (*arrow*). Adjacent right lower lobe pulmonary vein (*arrowhead*) is also seen. *RMPA* right main pulmonary artery

coronal and sometimes oblique MIP reconstructions are routinely obtained for the evaluation of PE in children (Fig. 4). Although MIP reconstructions can be helpful for detecting PE, review of multiplanar MIP reconstruction alone is less accurate than axial imaging because of partial volume artifact and masking effect by dense contrast agent within the vessel lumen from the MIP technique [15].

Iodine (perfusion) map imaging

Dual-energy CT is useful for PE imaging because it allows for both functional and high-resolution anatomical evaluation of the pulmonary vasculature and perfusion. Dual-energy CT perfusion imaging generates iodine pulmonary perfusion maps by exploiting the different energy characteristics of lung parenchyma and iodinated intravenous contrast agent, reflecting the iodine distribution within the lung parenchyma at the time of acquisition. Although the optimal time point to acquire pulmonary perfusion images should theoretically be during maximal lung parenchymal enhancement, acquisition of dual-energy CT images at the point of maximal pulmonary arterial enhancement is usually
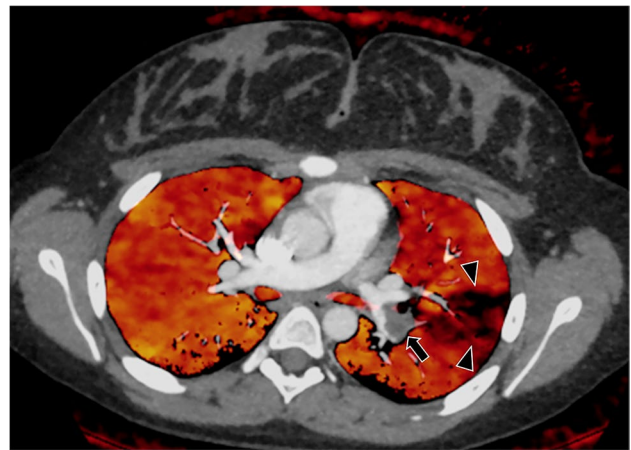

Fig. 5 Acute pulmonary embolism on axial iodine (perfusion) map CT image in a 14-year-old girl who presented with left-side chest pain and shortness of breath. Dual-energy computed tomography pulmonary angiography (CTPA) with generation of iodine maps is performed for every child as per institutional protocol when evaluating for pulmonary embolism. Axial iodine perfusion map CT image shows a perfusion defect (*arrowheads*) in the left lung as well as a filling defect (*arrow*) in the left main pulmonary artery

prioritized during CTPA for detecting filling defects (direct signs) of PE. Importantly, pulmonary parenchymal perfusion defects on CT perfusion have been shown to correlate well with nuclear medicine scans (Fig. 5) [16, 17]. One important benefit of dual-energy CT is the potential for reducing the dosage of IV contrast administered, which leads to decreased risk for nephrotoxicity in vulnerable pediatric patients, many of whom have suboptimal renal function. Furthermore, dual-source dual-energy CT scanners allow for alternating radiation outputs at a lower kVp, thereby having the added benefit of reducing the overall radiation dose to the child. At the authors' pediatric institution, CT iodine perfusion maps in axial and coronal planes are part of the standard post-processing technique for PE imaging. It is important to note that our institution uses predominantly dual-source dual-energy CT. For institutions that predominantly use single-source split-filter dual-energy CT, the utility of dual-energy CT and iodine mapping for PE evaluation should be considered on an individual basis, based on a study published by Petritsch and colleagues [18] indicating that iodine maps generated by single-source dual-energy CT have lower quality and higher radiation dosage.

Magnetic resonance imaging

Although MRI is an attractive alternative to CT in the pediatric population because it avoids ionizing radiation, several factors, including long scan times, relatively high cost and lack of widespread availability, limit the use of MRI as a standard alternative to CPTA for detecting PE. However, in select cases where ionizing radiation or iodinated contrast

agent must be avoided, MRI might offer some diagnostically useful information, although the sensitivity and specificity are not comparable to CTPA. Furthermore, MRI has decreased sensitivity for the detection of PE because of its intrinsically lower spatial resolution and susceptibility to artifacts, including motion, parallel imaging and truncation artifacts, that can markedly limit visualization and detection of segmental and subsegmental pulmonary emboli, which account for the majority of PEs, especially in children [18]. Additionally, MRI provides a poorer evaluation of the lung parenchyma compared with CT, making it less sensitive in the assessment of alternative diagnoses and other secondary findings. More recent technological advances in MRI including decreased scan times have reduced some disadvantages, increasing the viability of MRI as an alternative imaging option.

Various protocols exist for the use of MR imaging in PE detection. High-resolution three-dimensional (3-D) contrast-enhanced MRI can be acquired in 20 s, whereas time-resolved contrast-enhanced MRI sequences can be acquired in less than 4 s [18]. In fact, Nagle and colleagues [19] have described a contrast-enhanced MR angiography protocol utilizing rapid heavily T1-weighted 3-D spoiled gradient echo (GRE) sequences that can be performed with acquisition times of less than 20 s, with a total scan time of less than 10 min.

At the authors' institution, we use a combination of pre-contrast MRI and post-contrast MR angiography sequences for evaluating PE in the pediatric population (Fig. 6). We use gadobutrol (Gadavist; Bayer Healthcare, Whippany, NJ) at 0.1 mmol/kg diluted with normal saline to a total of 30 mL and injected at 1.5 mL/s. This injection rate and volume ensure uniform bolus throughout the pulmonary arterial system during k-space acquisition. A technique similar to CT bolus tracking is used to trigger k-space acquisition, using rapid 2-D gradient echo acquisitions at the ROI drawn over the main pulmonary artery until a signal threshold of approximately 20%. Depending on clinical need, delayed sequences can also be acquired to evaluate lung parenchymal enhancement for perfusion defects as secondary signs of PE. In addition, a motion insensitive sequence, such as periodically rotated overlapping parallel lines with enhanced reconstruction (PROPELLER; GE Healthcare, Waukesha, WI), BLADE (Siemens Healthcare, Erlangen, Germany), MultiVane (Philips Healthcare, Best, the Netherlands), RADAR (Hitachi, Tokyo, Japan) and JET (Canon Medical Systems, Tustin, CA), can be used to obtain high-quality anatomical information of the lung parenchyma.

Various studies have reported sensitivities ranging from 75% to 100% and specificities from 95% to 100% [20, 21]. However, one caveat is that sensitivity and specificity drastically drop in MR angiography studies that are deemed technically inadequate [22]. The proportion of MR angiography deemed technically inadequate has varied from 11% of
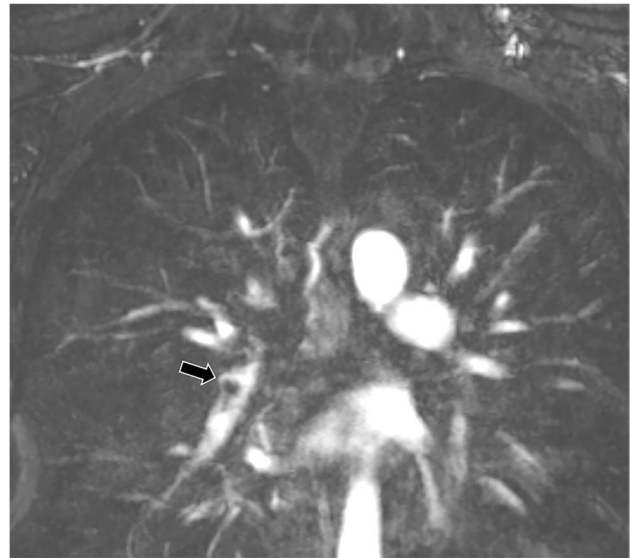

Fig. 6 Acute pulmonary embolism in a 19-year-old woman who presented with chest pain and right upper extremity deep venous thrombosis. Coronal MR angiography image shows a filling defect (*arrow*), consistent with pulmonary embolism in the right lower lobe segmental artery

studies at some centers to 52% at others [17]. In the pediatric population, where many children are sedated for MR angiography PE imaging, these numbers might be significantly different and are worthy of future study. As an alternative to sedation with breath-holding sequences, various free-breathing protocols have been developed for pediatric cardiac MRI/MR angiography. While less extensively studied for PE evaluation in children, free-breathing protocols, with the trade-off of longer scan times, have potential value in reducing the need for sedation when evaluating for PE in the pediatric population and are also worthy of further investigation. The utility of non-contrast MR angiography techniques for evaluating PE in the pediatric population has not been extensively studied and thus is another subject worthy of further investigation.

Imaging evaluation: pearls and pitfalls

The interpreting radiologist must be aware of and comment on artifacts or limitations that can impact the quality of the CTPA study, including respiratory motion, heterogeneous contrast mixing, poor bolus timing, photon starvation (i.e. one source of streak artifact) and beam hardening (e.g., streak artifact from dense contrast material within the superior vena cava) (Fig. 7). The interpreting radiologist benefits from pre-established window and levels for vasculature, soft tissues and lungs for complete review of CTPA images. When approaching a CTPA study for the evaluation of PE,
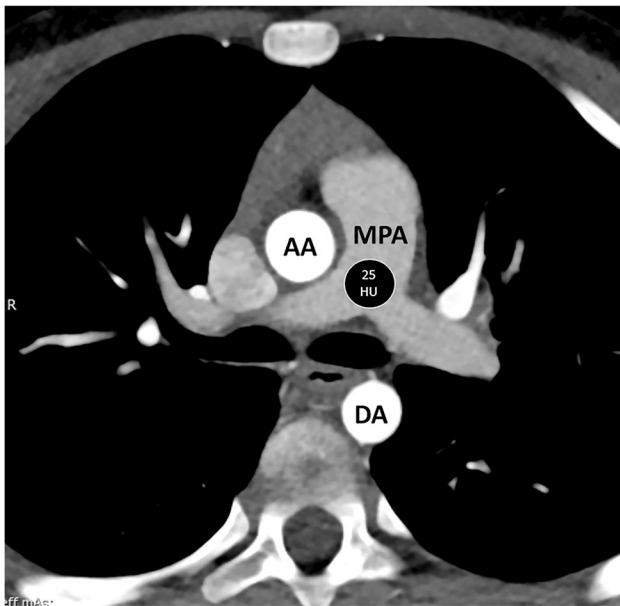
Fig. 7 Computed tomography pulmonary angiography (CTPA) with suboptimal image-quality caused by poor bolus timing. Axial enhanced CT image in a 12-year-old boy shows suboptimal contrast opacification of the pulmonary artery, with mean attenuation of 25 Hounsfield units (HU) in the main pulmonary artery (*MPA*). *AA* ascending aorta, *DA* descending aorta

the MP angiography should always be carefully checked for adequate contrast opacification. As a useful guideline for assessing MP angiography opacification, one might use the following: good (>250 HU), adequate (200–250 HU), limited (150–200 HU), inadequate (100–150 HU) and non-diagnostic (<100 HU). The pulmonary artery should then be traced respectively to the right main branch, the right upper lobar branch and its segmental and subsegmental branches, and the right middle and lower branches followed

by their respective segmental and subsegmental branches. The same would then be repeated with the left pulmonary artery branches. MPR and MIP images should be used to verify findings and for a second look. The heart should be evaluated for size, chamber opacification and pericardial effusion. Last, the extravascular structures, such as lungs, should be carefully evaluated for secondary abnormalities related to PE, including pulmonary infarcts, which can be also confirmed on iodine (perfusion) map imaging with dual-energy CT.

Imaging findings of pediatric pulmonary embolism

Advanced cross-sectional imaging offers high anatomical detail to allow for detection of direct and indirect imaging findings of acute and chronic PE as well as findings of alternative diagnoses in pediatric patients with negative CTPA studies, which are described in the following sections.

Direct imaging findings of acute pulmonary embolism

Direct findings of acute PE can be separated into three categories: (1) occlusive thrombus (Fig. 8), (2) central non-occlusive thrombus (Fig. 9) and (3) eccentric non-occlusive thrombus (Fig. 10). Occlusive thrombus appears as an expansile filling defect with abrupt non-opacification of the pulmonary vessel, which persists to the branch vessels. Central non-occlusive thrombus appears as an expansile filling defect in a partially opacified vessel or non-opacified vessel containing opacified branch vessels and must be present on two or more slices and in different planes. Eccentric non-occlusive thrombus should form an acute angle with the vessel wall and follow the other criteria
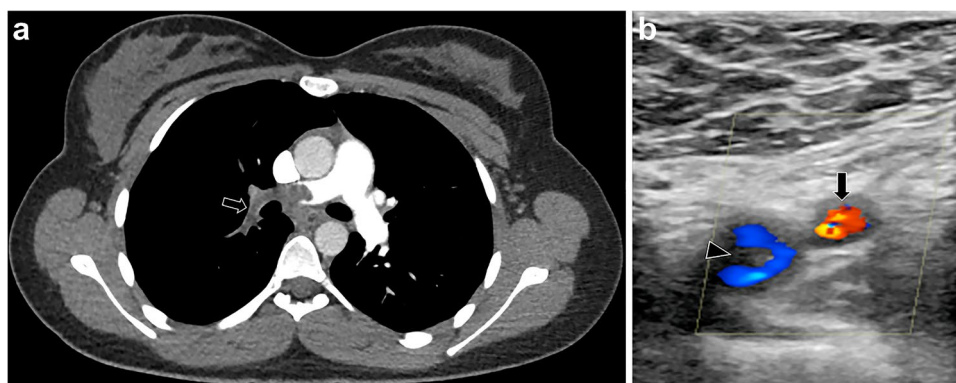

Fig. 8 Occlusive acute pulmonary embolism in a 14-year-old girl who presented with acute-onset shortness of breath, cough and right-side chest pain. **a** Axial enhanced CT image shows an acute occlusive pulmonary embolism (*arrow*) in the main pulmonary artery extending to the lobar pulmonary artery. **b** Transverse color Doppler US image demonstrates a non-occlusive thrombus (*arrowhead*) in the left external iliac vein. Adjacent left external iliac artery is also noted (*arrow*)
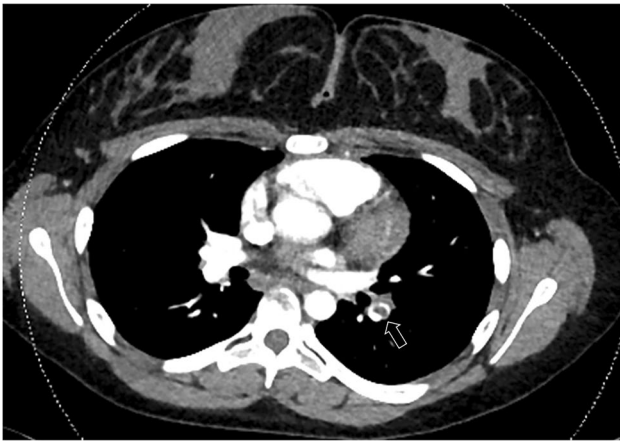
Fig. 9 Central non-occlusive thrombosis in a 17-year-old girl with obesity and elevated estrogen level. She presented with acute shortness of breath. Axial enhanced CT image shows a central non-occlusive pulmonary embolism (*arrow*) presenting as a filling defect in a partially opacified right lower lobe pulmonary artery
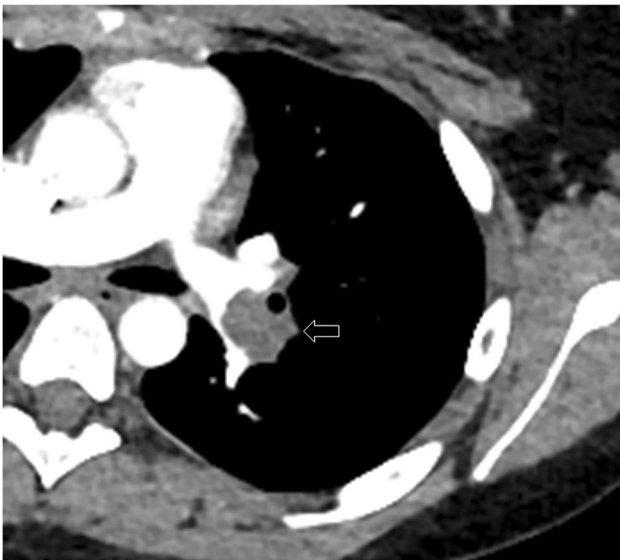

Fig. 10 Eccentric non-occlusive thrombosis in a 14-year-old girl who presented with shortness of breath. Axial enhanced CT image shows an eccentric non-occlusive pulmonary embolism (*arrow*) in the left main pulmonary artery forming an acute angle with the vessel wall

of central non-occlusive thrombus. The distribution of PE in children is similar to that in adults, with the majority localized to the lobar and segmental pulmonary arteries 26–39% and 35–52%, respectively, in the pediatric population [23].

Direct imaging findings of chronic pulmonary embolism

Direct imaging findings of chronic PE are variable and most frequently defined as thrombus persisting in the same vessel

for more than 3 months [19]. On CT, chronic PE can appear as a crescent-shape filling defect that forms an obtuse angle with the vessel wall. Other findings suggesting chronic PE include intraluminal webs or septations, arterial wall thickening and irregular lumen and, less often, calcified thrombus.

Indirect imaging findings of pulmonary embolism

Eponymous indirect radiographic signs of acute PE include: (1) Fleischner sign (prominent asymmetrical proximal pulmonary artery), (2) Hampton hump (peripheral pleural-based opacification that correlates to wedge-shape opacities on CT in the setting of a pulmonary infarct) and (3) Westermark sign (focal region of oligemia–paucity of pulmonary vessels). Although these eponymous signs lack significant sensitivity on radiographs, their correlates on CT imaging can be useful indirect findings of acute PE. Peripheral wedge-shape consolidation has been demonstrated to be the most common indirect imaging feature on CTPA studies in the pediatric population (Fig. 11) [24]. Other significant indirect imaging findings of acute PE include signs of right heart strain — e.g., interventricular septal flattening or concavity into the left ventricle (LV), contrast reflux into the inferior vena cava (IVC)/hepatic veins, and the LV/right ventricle (RV) diameter ratio — although studies evaluating the accuracy and prognostic value of these parameters demonstrate mixed results in the adult population [25–30].
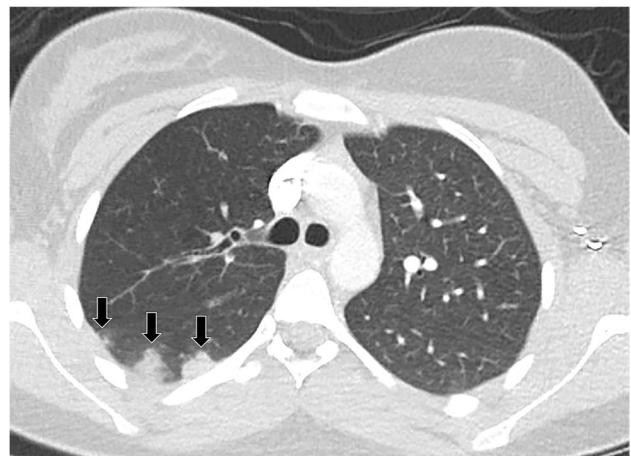

Fig. 11 Pulmonary infarcts, which are indirect CT findings of pulmonary embolism, in a 17-year-old girl with right-side pulmonary embolism. Axial lung window CT image shows several peripherally located and wedge-shape opacities (*arrows*) in the right lung, consistent with pulmonary infarcts. Also note the decreased number and caliber of pulmonary arteries in the right lung in comparison to left lung without pulmonary embolism
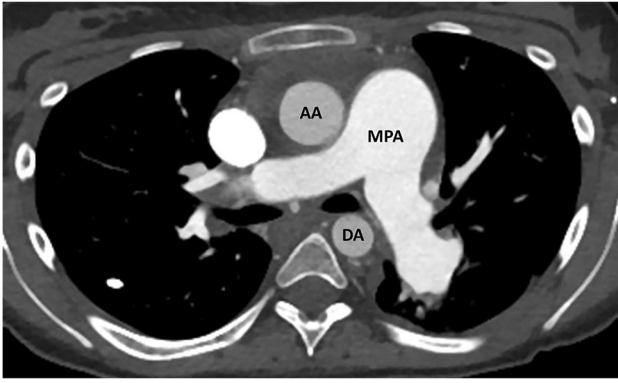
Fig. 12 Idiopathic pulmonary hypertension as an alternative diagnosis in negative computed tomography pulmonary angiography (CTPA) in a 14-year-old girl who presented with progressively worsening dyspnea, fatigue, syncope and chest pain. Axial enhanced CT image shows markedly enlarged pulmonary arteries and normal-size aorta. Subsequently obtained conventional pulmonary arteriography confirmed the diagnosis of pulmonary hypertension. No pulmonary embolism was noted in the pulmonary arteries on CTPA study. *AA* ascending aorta, *DA* descending aorta, *MPA* main pulmonary artery

Alternative diagnoses in negative computed tomography pulmonary angiography studies

In the case of both negative and inconclusive cases when assessing for PE on CTPA studies, the interpreting radiologist should entertain the possibility of alternative diagnoses. In a study conducted by Lee and colleagues [24] using a sample size of 96 pediatric CTPA studies, the authors demonstrated that only 41% of the studies were normal, whereas a plethora of alternative diagnoses were identified in the remaining 59% of cases, with pneumonia and atelectasis as the leading diagnoses in 77% of the cases showing positive findings. Other positive findings, while less common, included malignancy, congenital heart disease, pulmonary hypertension, pericardial effusion, rib fractures, fat embolism and right atrial thrombus (Fig. 12) [24].

Conclusion

Pulmonary embolism, which can be a life-threatening condition, has been recognized to be more prevalent than initially thought in the pediatric population. In addition, PE is receiving special attention because of the increased incidence of SARS-CoV-2 infection in children and the associated cardiovascular and prothrombotic complications of acute coronavirus disease 2019 (COVID-19) and MIS-C. CTPA is the imaging modality of choice for detecting pediatric PE and optimization of CT technique is crucial to maximizing detection of PE in children. Although less sensitive, there is a growing role for MRI/MR angiography as a cross-sectional imaging modality; however, the sensitivity is decreased compared to CTPA. Clear understanding of imaging techniques including patient preparation and characteristic imaging findings is essential for optimizing detection of pediatric PE, which, in turn, leads to optimal pediatric patient care.

Declarations

Conflicts of interest None

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