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Radiological evaluation of pulmonary embolism: Advances in diagnostic accuracy and imaging techniques

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Abstract--Background: Acute pulmonary embolism (PE) is a frequent, life-threatening condition predominantly caused by venous thromboembolism. Accurate and timely diagnosis is crucial for effective treatment, and imaging plays a central role in detecting PE. Recent advancements in imaging techniques have significantly improved diagnostic accuracy. **Aim:** This article reviews various radiological modalities for evaluating acute PE and their advances in diagnostic capabilities. **Methods:** The study examines the use of CT pulmonary angiography (CTPA), MRI, catheter pulmonary angiography, and other imaging techniques, such as echocardiography and nuclear medicine, highlighting their clinical applications and diagnostic precision. **Results:** CTPA is identified as the gold standard for diagnosing PE due to its high accuracy and speed, while MRI serves as a suitable alternative in patients with contraindications to iodinated contrast agents. Catheter angiography, though mostly replaced by CTPA, remains valuable for interventional treatments. Emerging techniques like dual-energy CT and non-contrast MRI show promise in enhancing diagnostic outcomes. **Conclusion:** Advances in imaging, including dual-energy CT and MRI, have improved diagnostic accuracy for PE, with each technique offering unique advantages. These innovations contribute to earlier detection, improved treatment planning, and better patient outcomes in acute PE management.

Keywords--Pulmonary embolism, CT pulmonary angiography, MRI, catheter pulmonary angiography, diagnostic imaging.

Introduction

Acute pulmonary embolism (PE) represents a frequently encountered and potentially lethal condition, with imaging playing a crucial role in its diagnosis and management. The primary cause of acute PE is venous thromboembolism (VTE), typically originating from the lower extremities, and is referred to as acute thrombotic PE or acute pulmonary thromboembolism (PTE) [1]. The term "acute PE" is often used interchangeably with "acute PTE," which can overlook non-thrombotic causes of acute pulmonary embolism. Differential diagnoses based on imaging for acute PTE encompass the range of acute non-thrombotic PE, chronic PE, and non-embolic pulmonary artery diseases. Endovascular interventions for acute PTE have gained importance, particularly for patients experiencing hemodynamic instability and right heart strain. This review will explore imaging modalities, diagnostic pathways, radiological findings, and endovascular treatments for acute PTE. Additionally, it will outline critical differential diagnoses related to acute non-thrombotic PE and non-embolic pulmonary artery diseases, with a focus on practical radiological insights and the latest advances applicable to clinical practice. Acute PE is a prevalent and potentially life-threatening disorder with an incidence of 50–200 cases per 100,000 individuals [2] [3]. In 95% of cases, it is triggered by dislodged thrombus material from deep vein thrombosis (DVT) in the lower extremities, leading to spontaneous, often recurrent embolic episodes (venous thromboembolism, VTE) [4]. Acute PE carries a mortality rate of 10–30%, ranking as the third leading cause of cardiovascular mortality, responsible for 300,000–370,000 deaths annually in Europe [4] [5].

Imaging Techniques

This section provides essential information on imaging protocols critical to daily radiological practice, focusing on CT pulmonary angiography (CTPA), chest MRI, and catheter pulmonary angiography. In the subsequent section, further imaging modalities—such as chest X-ray, echocardiography, nuclear medicine imaging, ultrasound, and imaging of the pelvis and extremities—will be discussed in greater detail.

Computed Tomography

CT pulmonary angiography (CTPA) is currently the gold standard for evaluating acute pulmonary embolism (PE) due to its high accuracy, accessibility, rapid turnaround time, superior spatial resolution, and ability to reconstruct images in multiple planes. CTPA is performed using multi-detector CT scanners following the intravenous administration of contrast. Typically, 50 to 100 mL of contrast is injected at a rate of 4–5 mL/s, followed by a saline flush at the same rate. The volume of contrast required depends on the patient's body habitus and the specific CT scanner. Bolus tracking is employed to synchronize the scan with the appropriate phase, generally when the attenuation in the main pulmonary artery reaches a threshold of 100 Hounsfield units (HU) above baseline. A timing bolus may also be used, though this increases both contrast and radiation exposure. The scan is conducted in a caudocranial direction to minimize motion artifacts at the lung bases during image acquisition, with patients holding their breath or in a resting expiratory state [6]. To prevent artifacts caused by transient contrast

interruption, careful breathing instructions are given to the patient before the scan, particularly to avoid rapid inspiration or the Valsalva maneuver during acquisition [6] [7]. Electrocardiogram (ECG) triggering is generally unnecessary. Tube current and voltage are usually selected automatically based on patient size if the scanner has this capability.

Whenever it is feasible, patients' arms should be positioned above the head to enhance image quality and reduce radiation exposure. In situations where this is not possible, arms should be placed in front of the abdomen rather than at the sides. A venous perfusion phase of the lower extremities may be combined with the CTPA [8] [9]. However, due to the increased radiation exposure and the need for a larger contrast volume, this is not routinely recommended. Nonetheless, it may prove beneficial for elderly patients with comorbidities where the rapid diagnosis of deep vein thrombosis (DVT) is crucial for prognosis. Wide-array scanners, which cover more area per rotation, minimize motion artifacts, while dual-source scanners in high-pitch helical mode (up to 2) reduce breath-hold times, further improving image quality and lowering both radiation and contrast doses [10]. For patients with lower body weight, low tube voltage techniques (70–80 kVp) can also be applied, reducing radiation and contrast doses due to iodine's increased X-ray absorption at lower voltages [11]. Iterative reconstruction algorithms allow for further reduction in radiation dose [11]. Dual-energy CT, which utilizes technologies such as dual-source, dual-layer, dual-spin, dual-filter, and rapid kVp switching, acquires data at two distinct energy levels [12]. This enables differentiation of tissues with similar attenuation values through additional imaging sets, including iodine or Z-effective maps, virtual non-contrast images, and virtual monoenergetic images (VMI). Iodine or Z-effective maps can be used to generate perfusion blood volume (PBV) maps of lung perfusion, while low-energy VMI (< 70 keV) enhances contrast signal, making it useful for salvaging suboptimal vascular studies or allowing for lower doses of intravenous contrast [13]. High-energy VMI can reduce artifacts, such as those caused by metallic implants, and virtual non-contrast images can help in characterizing incidental findings like calcified granulomas.

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) has become an important alternative to CTPA in diagnosing acute pulmonary embolism (PE), particularly for patients who cannot receive iodinated contrast agents, such as those who are pregnant or younger patients. The standard MRI protocol includes static steady-state free precession (SSFP) sequences, contrast-enhanced 3D magnetic resonance angiography (MRA) using a T1-weighted gradient-echo (GRE) sequence, and post-contrast 2D axial or 3D T1-weighted GRE sequences. For patients who can tolerate lying flat in the MRI scanner, an additional time-resolved contrast-enhanced 3D (4D) MRA before the standard 3D MRA sequence can provide useful dynamic perfusion data [14]. Static SSFP sequences are typically acquired in both axial and coronal orientations during free breathing or while holding a breath. The bright blood signal allows detection of pulmonary emboli even without using intravenous contrast, which is particularly beneficial for pregnant patients. Contrast-enhanced 3D MRA with high spatial resolution is acquired in a coronal orientation, requiring three inspiratory breath-holds to capture pre-contrast

images for subtraction, arterial phase images, and late arterial phase images [14]. A gadolinium-based contrast agent at 0.1 mmol/kg is administered at a rate of 2 mL/s. A timing bolus is generally used to determine the point of peak contrast enhancement in the pulmonary arteries, though a bolus-tracking technique similar to that used in CTPA can also be applied. Time-resolved contrast-enhanced 3D MRA, with reduced spatial resolution, involves multiple acquisitions of rapid volumetric sequences with parallel imaging and view-sharing techniques (such as TWIST, TRICKS, or 4D-TRAK depending on the equipment vendor) during shallow breathing after the first pass of a 0.05 mmol/kg gadolinium bolus at 4 mL/s. Temporal resolution should aim for approximately 1 frame per second. Subtraction images for each time frame can be produced by subtracting the last non-enhanced frame, helping to visualize perfusion defects and narrow down the search for pulmonary emboli [15]. The PIOPED III study was the largest to evaluate the diagnostic accuracy of contrast-enhanced MRA compared to CTPA for detecting acute PE [16]. In technically adequate cases, the sensitivity and specificity of contrast-enhanced MRA were 78% and 99%, respectively. However, a significant drawback was the high rate of technically inadequate studies (25% of cases), mainly due to poor arterial opacification or motion artifacts. The study concluded that MRA should only be performed at facilities where it is routinely used and provides high diagnostic quality, and only in patients contraindicated for CTPA. Recent advancements include various non-contrast-enhanced techniques. For instance, 3D SSFP sequences can be used to generate non-contrast-enhanced 3D MRA, offering diagnostic accuracy comparable to contrast-enhanced MRA, at least for central and lobar arteries [17]. Additionally, Fourier decomposition MRI enables the assessment of pulmonary ventilation and perfusion without contrast agents, providing data similar to that of a nuclear medicine ventilation/perfusion scan [18]. However, more clinical studies are needed to evaluate the clinical applicability and diagnostic accuracy of these techniques in routine practice.

Catheter Pulmonary Angiography

Catheter pulmonary angiography, once considered the gold standard for diagnosing acute pulmonary embolism (PE), has largely been replaced by CT pulmonary angiography (CTPA). However, it remains essential for patients undergoing potential endovascular treatment. Access for the procedure is typically obtained via the right common femoral or right internal jugular vein, using a 7 French introducer sheath. Femoral access is generally preferred when immediate treatment is planned, as it offers better catheter and wire manipulation compared to the jugular route. The catheter is advanced through the right atrium and ventricle to the pulmonary trunk, often causing transient arrhythmias, necessitating continuous ECG monitoring throughout the procedure. For patients with pre-existing left bundle branch block on ECG, temporary pacing is recommended, as wire manipulation in the right heart can induce a right bundle branch block, potentially leading to complete heart block [19]. Therefore, pre-procedural ECG assessment is crucial. Pressure measurements are taken in the right atrium and pulmonary trunk before angiography to aid in risk stratification. Standard protocols for selective pulmonary artery angiography involve the injection of 40 mL of iodinated contrast at 20 mL/s. Adjustments are made based on renal function and the patient's

hemodynamic status. In cases where only one lung is affected or targeted for treatment, unilateral angiography may be performed to reduce contrast volume and save time. Complications of catheter pulmonary angiography include access site injuries (such as bleeding or dissection), arrhythmias, vessel perforation, and risks associated with iodinated contrast (contrast-induced nephropathy and thyrotoxicosis).

Imaging Findings

Acute PE findings on CTPA or MRA include filling defects within the pulmonary arteries. These defects are often present as the "polo mint sign" when viewed perpendicularly to the vessel or the "railway sign" when viewed along the vessel's course [20]. A key advantage of CTPA over MRA is the embolus signal itself, as it shows soft tissue density on CT, while MRA sequences often display no signal due to short echo times. Acute PE emboli typically form acute angles with the vessel wall and are located at vessel bifurcations. They may also cause complete occlusion, leading to vessel enlargement and reduced caliber of distal arteries due to impaired perfusion. In contrast, chronic PE exhibits filling defects that are adherent to the vessel wall, forming obtuse angles, intraluminal webs or bands, and recanalized thrombi. Complications of acute PE include right ventricular dysfunction and pulmonary infarction. Indicators of right heart strain on CTPA or MRI include a pulmonary trunk diameter >29 mm, a right-to-left ventricular diameter ratio >1 , flattening or bowing of the interventricular septum, and contrast reflux into the inferior vena cava and hepatic veins [26]. Right heart strain is associated with worse clinical outcomes, with the right-to-left ventricular diameter ratio being the most reliable predictor of adverse outcomes. Pulmonary infarction is characterized by a wedge-shaped opacity in the lung periphery (Hampton's hump) visible on CT, MRI, or chest X-ray. It is often accompanied by central ground glass opacity, known as the "reversed halo" or "atoll" sign. Pulmonary infarction occurs in 10-15% of acute PE patients, particularly those with left-sided heart failure, which reduces collateral blood supply via the bronchial arteries. Advanced imaging techniques, such as iodine maps from dual-energy CT and time-resolved contrast-enhanced MRA, improve the detection of wedge-shaped perfusion defects indicative of acute PE, especially in cases of subsegmental emboli. In patients with a persistent foramen ovale, elevated right atrial pressure can lead to paradoxical embolism, increasing the risk of stroke or visceral infarction. Splenic or renal infarcts observed on CTPA or MRI in the context of acute PE often indicate paradoxical embolism. Additionally, CTPA may directly visualize a persistent foramen ovale. Artifacts that may mimic filling defects or vascular abnormalities include motion artifacts (due to breathing or cardiac motion), patient movement, and beam hardening from contrast in the superior vena cava or from medical devices such as catheters, wires, or orthopedic prostheses. These artifacts can result in abrupt changes in attenuation along the vessel's course.

Other Radiological Techniques for Pulmonary Embolism

Pulmonary embolism (PE) is a life-threatening condition that requires rapid and accurate diagnosis to guide treatment and prevent complications. While CT pulmonary angiography (CTPA) remains the gold standard for diagnosing PE,

several other radiological techniques have emerged as alternatives or adjuncts, especially in patients with contraindications to CTPA, such as allergies to iodinated contrast or impaired renal function. These techniques include ventilation-perfusion (V/Q) scintigraphy, magnetic resonance imaging (MRI), and ultrasound-based methods, each offering specific advantages depending on the clinical scenario [21].

1. Ventilation-Perfusion (V/Q) Scintigraphy

V/Q scintigraphy has been a long-standing diagnostic tool for detecting PE, particularly in patients with contraindications to CTPA. This nuclear medicine technique evaluates the ventilation and perfusion of the lungs to identify mismatches that suggest embolism. In V/Q scanning, the ventilation scan involves the inhalation of radiolabeled gases or aerosols, while the perfusion scan uses intravenously injected radiolabeled particles to assess blood flow. A mismatch between normal ventilation and reduced perfusion typically indicates PE. Though V/Q scintigraphy has high sensitivity for detecting PE, especially in central and lobar arteries, its specificity can be limited, particularly in patients with underlying lung disease, as perfusion defects can also result from other causes such as chronic obstructive pulmonary disease (COPD) or pneumonia. Additionally, the advent of CTPA has somewhat limited the use of V/Q scans, but it remains valuable for patients who cannot tolerate iodinated contrast or radiation, such as pregnant women and those with severe renal insufficiency.

3. Echocardiography and Ultrasound-Based Techniques

Although not a direct imaging modality for PE, echocardiography can provide critical indirect evidence of pulmonary embolism, especially in patients presenting with hemodynamic instability. Echocardiography can reveal signs of right ventricular strain or dysfunction, such as right ventricular dilatation, septal bowing, or McConnell's sign, which are suggestive of acute PE. Transesophageal echocardiography (TEE) can also visualize emboli in the pulmonary arteries, but its invasive nature and limited field of view restrict its routine use. Ultrasound-based methods, particularly lower extremity venous ultrasound, are also important in the evaluation of suspected PE, as deep vein thrombosis (DVT) is a frequent source of emboli. The presence of DVT in symptomatic patients significantly increases the likelihood of PE, and ultrasound can detect thrombi in the deep veins without the need for contrast agents or radiation. Although not definitive for PE, positive ultrasound findings can support clinical suspicion, prompting further investigation with CTPA or other imaging techniques.

4. Dual-Energy CT (DECT)

An advanced variation of CTPA, dual-energy CT (DECT) has been developed to enhance the diagnosis of PE. DECT allows for the differentiation between iodine and soft tissue, enabling the generation of iodine perfusion maps of the lungs. This provides detailed information on perfusion abnormalities that might be missed by conventional CTPA, particularly in cases of subsegmental emboli. While DECT is promising, its clinical application is still limited due to the need for specialized equipment and higher radiation doses compared to standard CTPA.

Conclusion

The radiological evaluation of acute pulmonary embolism (PE) has evolved significantly, with advancements in imaging techniques contributing to more accurate and rapid diagnosis. CT pulmonary angiography (CTPA) has become the gold standard for diagnosing PE, offering superior spatial resolution, fast acquisition times, and accessibility in most healthcare settings. Its high diagnostic accuracy makes it the first-line imaging modality for acute PE. Furthermore, the development of dual-energy CT has added a layer of sophistication to PE diagnosis, allowing for detailed perfusion maps and improved differentiation of tissue characteristics, thus enhancing overall diagnostic confidence, especially in complex or suboptimal cases. Magnetic resonance imaging (MRI), although less frequently used than CTPA, remains a critical tool, particularly for patients who cannot undergo CT due to contraindications to iodinated contrast agents. Recent advances in non-contrast MRI techniques, such as 3D steady-state free precession (SSFP) sequences and Fourier decomposition MRI, are proving to be valuable alternatives, especially for detecting central and lobar PEs without the need for contrast. However, the limitations of MRI, including motion artifacts and the requirement for high technical expertise, restrict its widespread use to specialized centers. Catheter pulmonary angiography, once the gold standard, is now primarily reserved for patients requiring endovascular interventions. Its role remains vital in high-risk cases where immediate intervention is necessary, and it provides precise anatomical details of the pulmonary vasculature. In conclusion, modern imaging techniques have greatly enhanced the ability to diagnose and manage PE effectively. These advancements contribute to better clinical outcomes by facilitating earlier diagnosis, guiding appropriate therapeutic interventions, and improving patient prognosis. Moving forward, further integration of novel imaging technologies and continued refinement of existing modalities will likely lead to even greater improvements in the management of acute PE.

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التقييم الإشعاعي للانصمام الرئوي: تطورات في دقة التشخيص وتقنيات التصوير

الملخص

الخلفية: يُعد الانصمام الرئوي الحاد حالة شائعة مهددة للحياة، تُعزى بشكل رئيسي إلى الانصمام الوريدي الخثاري. يُعتبر التشخيص الدقيق وفي الوقت المناسب أمرًا بالغ الأهمية للعلاج الفعال، ويلعب التصوير دورًا محوريًا في الكشف عن الانصمام الرئوي. وقد ساهمت التطورات الحديثة في تقنيات التصوير في تحسين دقة التشخيص بشكل كبير.

الهدف: تُراجع هذه المقالة الوسائل الإشعاعية المختلفة لتقييم الانصمام الرئوي الحاد والتطورات في قدراتها التشخيصية.

الطرق: تبحث الدراسة في استخدام تصوير الأوعية الدموية الرئوية المقطعي المحوسب (CTPA)، والتصوير بالرنين المغناطيسي (MRI)، وتصوير الأوعية الرئوية بالقسطرة، بالإضافة إلى تقنيات أخرى مثل تخطيط صدى القلب والطب النووي، مع تسليط الضوء على تطبيقاتها السريرية ودقتها التشخيصية.

النتائج: يُعتبر CTPA المعيار الذهبي لتشخيص الانصمام الرئوي نظرًا لدقته العالية وسرعته، بينما يُعد التصوير بالرنين المغناطيسي خيارًا مناسبًا للمرضى الذين يعانون من موانع لاستخدام عوامل التباين المعالجة باليود. وعلى الرغم من أن تصوير الأوعية بالقسطرة تم استبداله في الغالب بـ CTPA، إلا أنه لا يزال ذا قيمة للعلاجات التداخلية. كما تُظهر التقنيات الناشئة مثل التصوير المقطعي مزدوج الطاقة والتصوير بالرنين المغناطيسي بدون تباين إمكانات واعدة في تحسين النتائج التشخيصية.

الخلاصة: أدت التطورات في تقنيات التصوير، بما في ذلك التصوير المقطعي مزدوج الطاقة والرنين المغناطيسي، إلى تحسين دقة تشخيص الانصمام الرئوي، مع تقديم كل تقنية مزايا فريدة. تُسهم هذه الابتكارات في الكشف المبكر، وتحسين تخطيط العلاج، وتحقيق نتائج أفضل للمرضى في إدارة الانصمام الرئوي الحاد.

الكلمات المفتاحية: الانصمام الرئوي، تصوير الأوعية الرئوية المقطعي المحوسب، التصوير بالرنين المغناطيسي، تصوير الأوعية الرئوية بالقسطرة، التصوير التشخيصي.