International Journal of Biomedicine 13(1) (2023) 20-25
http://dx.doi.org/10.21103/Article13(1)_RA3

REVIEW ARTICLE

INTERNATIONAL JOURNAL OF BIOMEDICINE

Comparative Overview of Different Radiological Imaging Techniques in the Diagnosis of Pulmonary Embolism

Zuhal Y. Hamd*

Radiological Sciences Department, College of Health & Rehabilitation Sciences, Princess Nourah bint Abdulrahman University, Riyadh 11671, Saudi Arabia

Abstract

Background: Imaging techniques such as chest X-ray (CXR), computed tomography pulmonary angiography (CTPA), ventilation-perfusion (V/Q) scintigraphy, and magnetic resonance imaging (MRI) are some methods used to detect and manage acute pulmonary embolism (PE). The aim of this review was a comparative analysis of the various imaging techniques used to evaluate PE.

Methods and Results: The incidence, distribution, clinical features, classification of PE and clinical assessment of the current methods for diagnosis of PE were discussed. CTPA is the gold standard for fast turnaround and accurate diagnosis. Additional probable reasons for sudden chest pain can also be learned through a CT scan. Lung perfusion anomalies can be identified and measured using dual-energy CT. Chest radiographs are only marginally beneficial, occasionally revealing PE or infarction signs, but are helpful in ruling out other possible causes of chest pain. These patients' ventilation-perfusion mismatches are evident in the V/Q scan, which has many grading schemes with conventional ranges from normal to high. While MRI, which is only available in specialist facilities and calls for higher degrees of competence, also offers accurate diagnosis.

Conclusion: Early diagnosis and treatment of PE is challenging due to asymptomatic conditions or overlapping symptoms. Diagnosis of PE in expectant mothers and those with suspected PE recurrence is typically difficult. Over-diagnosis and overtreatment, particularly regarding sub-segmental PE, and the lowered clinical suspicion threshold remain a major concern in PE diagnosis. The routine use and integration of the above diagnostic techniques need to be encouraged in clinical practice to overcome the diagnostic hurdles. The introduction of new diagnostic techniques or improved risk stratification processes might enhance the management of PE.(**International Journal of Biomedicine. 2023;13(1):20-25.**)

Keywords: pulmonary embolism • magnetic resonance imaging • computed tomography pulmonary angiography • ventilation-perfusion scan • chest radiographs

For citation: Hamd ZY. Comparative Overview of Different Radiological Imaging Techniques in the Diagnosis of Pulmonary Embolism. International Journal of Biomedicine. 2023;13(1):20-25. doi:10.21103/Article13(1)_RA3

Abbreviations

CT, computed tomography; **CTPA**, CT pulmonary angiography; **CXR**, chest X-ray; **DVT**, deep vein thrombosis; **MRI**, magnetic resonance imaging; **PE**, pulmonary embolism; **SPECT**, single-photon emission computed tomography; **V/Q**, ventilation-perfusion; **VTE**, venous thromboembolism.

Introduction

Venous thromboembolic disease (VTE) includes deep vein thrombosis (DVT) and pulmonary embolism (PE) as two distinct but often associated entities. Deep venous thrombi that have detached and embolized to the pulmonary circulation lead to the incidence of PE.[1] As a result of the pulmonary vascular blockage, perfusion and gas transfer are compromised. More typically than the upper lobes, the lower lobes of the lungs are impacted, and bilateral lung participation is prevalent. Smaller emboli obstruct the peripheral arteries, while larger emboli compress in the primary pulmonary artery. A pulmonary infarction caused by peripheral PE might be seen as intra-alveolar bleeding. Dead zone ventilation results from pulmonary artery occlusion since alveolar ventilation is greater than pulmonary capillary blood flow. Vascular obstruction of the arteries raises pulmonary vascular resistance, which exacerbates the imbalance between ventilation and perfusion. Additionally, serotonin and thromboxane, two humoral mediators produced by active platelets, can elicit vasoconstriction in unaltered lung areas. When the pulmonary artery systolic pressure increases, the right ventricular afterload also increases, leading to right ventricular dysfunction. As right ventricular failure develops, a diminished left ventricular filling may develop. Due to insufficient coronary artery filling, myocardial ischemia may advance quickly, potentially leading to hypotension, syncope, electromechanical dissociation, or abrupt death.[2]

PE is a high early-mortality-rate, acute cardiovascular disorder that can result in acute right ventricular (RV) failure, a life-threatening condition.[3] It is the third leading cause of cardiovascular-related deaths worldwide. Therefore, rapid diagnosis and prompt therapeutic intervention are necessary for optimal management of the condition. Patients may remain asymptomatic or have symptoms that also occur in other cardiopulmonary diseases; the severity of the symptoms depends upon the duration and the level of the thrombus as well as the previous history of the patient. Diagnosis of PE still remains a challenge, wherein, under- and overdiagnosis may have serious consequences.[4] Ruling out PE is significant due to the risk of bleeding upon anticoagulation therapy and the costs of treatment and management.[5] Diagnosis relies on a combination of clinical assessment, diagnostic thoracic imaging, and the D-dimer test, each of which has its own benefits and limitations. Therefore, initial tests that are lower in cost and risk are conducted to exclude PE efficiently, whereas imaging tests are carried out on patients in whom PE could not be excluded upon initial assessment. Currently, the most recommended imaging technique by clinicians is CT pulmonary angiography (CTPA). However, for patients with renal insufficiency, CT is contraindicated, and lower limb venous compression ultrasound or V/Q scans are the diagnostics of choice. More recently developed novel diagnostic tests such as V/Q SPECT seem to be promising and accurate and a potential substitute for CTPA. However, further studies on PE management outcomes are warranted before it finds implementation in clinical practice. In this article, we aim to review the various diagnostic imaging techniques for PE that are well-established or novel and to provide a comparative analysis of these methods that may be used in diagnostic management tailored to patient requirements.

Incidence, distribution, classification, and clinical features of PE

Dislodging a deep vein thrombus/clot from the lower limbs can lead to PE development. The thrombus then moves to the arterial lung circulation and lodges itself, thus causing a partial or complete block.[6] Acute onset chest pain presented in the emergency room is often caused by acute PE that occurs in 0.2% of individuals affected by VTE. About 5%–8% of the US population who have inherited thrombophilia are more at risk of VTE. PE remains the third leading cause of cardiovascular-related deaths, causing an annual hospitalization of 250,000 individuals in the USA alone.[7-9] It is found to occur in higher numbers in males than females and can lead to chronic thromboembolic pulmonary hypertension (CTEPH) as a long-term consequence.[10,11] Recently, the incidence of PE has increased, although deaths have decreased despite the high mortality rates associated with PE.[12] Recurrent PE is seen in up to 30% of individuals within 10 years of being affected with VTE, and half of them ultimately develop long-term post-thrombotic syndrome.[8] Hypertension, malignancy, obesity, and recent surgery or immobilizations are among the risk factors predisposing one to DVT and, eventually, PE.[13] The clinical features of acute PE vary among individuals. A large majority of patients affected with PE may remain asymptomatic, whereas other patients may be presented with sudden death. Clinical features of acute PE commonly include dyspnea, chest pain, hypotension, cough, tachycardia, and hemoptysis. Cardiac arrest, shock, and hypotension are presented in patients with massive PE. Patients with right heart strain show notched S wave in lead V1, changes in S1Q3 and S1Q3T3 pattern, inverted T waves, and right bundle branch block in ECG.[14] Proximal DVT causes symptoms that include edema, pain, erythema, and swelling in the lower extremities. The Wells score[15] or the Geneva score helps stratify PE. Stratification is based on a three-tier model (>6, high risk; 2–6, moderate risk; 0–1, low risk) that helps classify risk reliably,[16] or a two-tier model (>4 PE likely; ≤4 PE unlikely) that recommends performing a D-dimer test on patients unlikely to have PE, in contrast to a CTPA being performed in patients likely to have PE.[17]

Clinical assessment and review of current methods for the diagnosis of PE

Suspected PE initially assessed using ECG or CXR that rules out any other cause requires further testing to confirm or exclude diagnosis with a high level of certainty to overcome the consequences of anticoagulation prescription or a missed PE diagnosis. More than two decades have gone into developing diagnostic strategies to manage PE safely and non-invasively. Imaging plays a crucial role in diagnosing and managing acute PE. However, increasingly available imaging techniques and their widespread use for precise diagnosis of PE as reflected by a decrease in the prevalence of PE among suspected patients,[18] raise public health questions that include costs and radiation hazards and treatment of very small clots that may not be clinically relevant. Therefore, D-dimer measurements and clinical probability assessment allow for ruling out PE in suspected patients without any imaging tests.

CTPA is a rapid procedure that accurately diagnoses PE and forms the first line of image modality. Other causes of acute chest pain can also be detected with CT, while dual-energy CT helps to detect and quantify lung perfusion abnormalities. Contrarily, CXR is used in evaluating other chest pain causes and can only occasionally detect PE or infarction. The V/Q scan detects ventilation-perfusion mismatches, while MRI, which is only available in specialized centers and requires expertise to be operated, provides a precise diagnosis of PE. V/Q scintigraphy was the first non-invasive procedure used to diagnose PE.[19-21] However, a high percentage of nondiagnostic scans result in complex diagnostic algorithms, thus decreasing acceptance of V/Q scintigraphy, compared to CTPA. Nevertheless, CTPA has drawbacks that include higher radiation dose, renal impairment, contraindications like an allergic response to iodine contrast media, and the risk of misdiagnosing non-clinically relevant PE.[4,22] In this field, in vivo characterization of the thrombus remains a crucial challenge.[23]

Comparative analysis of the various radiological imaging techniques employed in PE analysis

Chest Radiograph

CXR helps to detect causes of acute chest pain that include pulmonary edema, pneumonia, or pneumothorax, but is not useful in PE diagnosis. However, some radiographic abnormalities specific to PE may be seen in acute PE patients. The Fleischner sign, which refers to an enlarged pulmonary artery, occurs post its distension due to the embolus that also causes pulmonary hypertension. The Westermark sign refers to regional oligemia due to PE, which has 92% specificity and 14% sensitivity in PE diagnosis. In pulmonary infarction, a Hampton hump may be seen and has 28% PPV, 76% NPV, 22% sensitivity, and 82% specificity. Other non-specific findings comprise vascular redistribution, elevated diaphragm, and pleural effusion.[24]

Computed tomography pulmonary angiography

CTPA forms the standard care for the diagnosis of PE in suspected patients and is used in clinical diagnostic algorithms.[9] PIOPED II trial indicates CTPA to have 83% sensitivity and 96% specificity in accurately diagnosing PE.[25,26] The advantages of CTPA include being rapid, minimally invasive, and readily available.[27] CTPA allows direct visualization of thrombus and can detect other etiologies causing shortness of breath as well as pain in the chest and coronary artery disease.[28] The risk of cancer owing to exposure to ionizing radiation is a concern of using CT; however, technical advances in protocols minimize the amount of ionizing radiation.[29] For patients with a poor glomerular filtration rate, the intravenous contrast material employed in CTPA may not be accepted due to its association with contrast-induced nephropathy (CIN).[30,31] Adverse events are low, ranging between 0.2% and 0.7%.[32,33] CTPA can detect sub-millimeter-sized, small sub-segmental pulmonary emboli and pleural effusion. A pulmonary infarct, a major consequence of acute PE, is characterized by a wedge-shaped, peripheral opacity consisting of a central ground glass and a rim of consolidation in CTPA.[34] In contrast, chronic PE is characterized by thrombus recanalization, calcification, intraluminal webs, and filling defects that adhere to the wall, forming concave surfaces and obtuse angles. The vessels in chronic PE exhibit abnormal tapering, are smaller than normal, and may be entirely cut off from the segmental vessel. Chronic PE demonstrates parenchymal changes that constitute band-like opacities, mosaic perfusion, and bronchial dilation.[35,36] Based on several parameters, CT helps to estimate risk-stratification and the severity of PE, such as clot burden, right heart strain, and lung perfusion. Flattening of the interventricular septum, increased right ventricle/left ventricular ratio, and reflux of contrast material into the hepatic veins and the inferior vena cava (IVC) are the features of right heart strain.[37] Scores such as the CT obstruction index and the CT severity score developed by Qanadli et al.[38] and by Mastora et al.,[39] respectively, are used to quantify the clot, but are not used in clinical practice routinely.[40,41] Recent technological advances in CT have made low doses of radiation and concentration contrast material in CTPA acquisition feasible. Based on the body mass index of a patient, radiation doses are minimized by using minimal tube voltage and tube current.[42] Tube current modulation based on the density and thickness of the imaged area can save 26% of the radiation dose.[43] Advanced iterative reconstruction algorithms that use hybrid techniques or statistical models mitigate image noise arising due to low tube current and voltage.[44] Low-dose CTPA, in conjunction with the reconstruction algorithm, yields similar quality to standard-dose CTPA.[45] Low voltage scans reduce the requirement of contrast material by 33% but maintain diagnostic accuracy and image quality.[46,47] Recently developed dual-source scanners permit rapid high-pitch CT acquisitions (up to 3.4) while removing gaps in data. The rapid acquisition reduces the radiation dose, volume of contrast material,[48,49] and motion artifact, allowing free-breathing CTPA studies,[50] and evaluation of the coronary arteries, aorta, and pulmonary vessels.[51] Recent CT methods use a combination of dual-source, dual-energy CT (DECT) and improved iodine detection to allow CTPA with minimal loads of contrast material, tube voltage, and tube current without substantial degradation in the quality of images.[52-54] The use of X-ray tube power and IR algorithms in advanced technologies may even allow high-pitch CTPA in a large patient population while eliminating noise.[55]

V/Q scintigraphy

This technology is a nuclear examination that makes use of a ventilation scanning procedure to determine the pattern of airflow in the lungs and a perfusion scan to map out the blood flow pattern. By analyzing images that demonstrate ventilation and perfusion in all parts of the lungs by employing radioactive tracers, the V/Q scan aids in the clinical decision process.[56]

In cases where CTPA is either impossible or inappropriate, a V/Q scan is preferable. These cases include women who are pregnant, and persons who have renal disease, are allergic to iodinated radiocontrast agents, or cannot accommodate a CT scanner. It exposes the individuals to a 50-times lower radiation dose. A systemic evaluation of 23 prospective trials found that in a sum total of 7000 patients in whom the clinical likelihood and D-dimer evaluation were ambiguous, a normal perfusion scan may be used to safely rule out PE.[19]

The V/Q scan is a safe treatment option that most patients tolerate well. But there are some potential pitfalls which include bruising, swelling, redness, and experiencing pain at the injection site; a radioactive, isotope-induced allergic response that is treatable; and radiation exposures to the fetus, particularly in the first trimester.[56]

One hour before the initiation of the study, a posterior-anterior and lateral chest radiograph is required. Nevertheless, in patients without deteriorating signs and symptoms, a chest radiograph taken 24 hours prior to the V/Q scans is generally acceptable. Regional ventilation is mapped using a variety of products, such as inert gases (81mKr, 133Xe), radiolabeled aerosols 99mTc-DTPA, and 99mTc-labelled technegas.[57]

Multiple imaging techniques are used, such as V/Q imaging with SPECT (V/Q), a regularly used protocol, and in uncommon circumstances, planar scintigraphy (V/Q) is also used. To prevent the transmission of SARS-CoV-2 during the COVID-19 epidemic, many facilities chose to perform perfusion-only scanning. Additionally, CT or CTPA may be coupled with V/Q.

Multidetector gamma cameras are used in SPECT to acquire the images and produce a three-dimensional version of the captured images. SPECT demonstrated greater sensitivity than the planar approach.[58] The V/Q SPECT is considered to be the second choice of the diagnostic test if the CTPA contrast and exposure to radiation are prohibited.[59] Low indetermination rate and higher reproducibility are two benefits of the aforementioned technique.[60] More sensitivity and specificity, novel methods of processing analytical data, and cutting-edge methods, such as V/Q ratio certification, are the added advantages of the said technique.[61]

For ventilation and perfusion imaging, a double gamma camera is used to acquire two-dimensional V/Q Planar image capture. Between the two consecutive scans, the patient needs to move as little as possible. When the V/Q SPECT seems not to be viable, at least four views are employed in this approach.[62] A significant disadvantage of the approach is its two-dimensional imaging. Additionally, following the embolic event, inaccurate diagnosis of segmental lung involvement, and difficulty in determining the severity of perfusion abnormalities are some of the other notable drawbacks.[4]

A low-dose CT scan is combined with functional SPECT imaging using the V/Q SPECT/CT Imaging Technique to offer more precise anatomical data. In actual practice, the perfusion scan is typically followed by the CT scan.[59] The biggest drawback of the technique is exposure to radiation. SPECT/CT has benefits that include V/Q mismatch situations, such as tumor, external vascular compression, or obstructive lung illness, and can be detected with greater accuracy than PE.[62] For non-embolic reasons, V/Q matching data seems to be better (pneumonia, pleural or pericardial effusion). Detection of PE cases is made possible where V/Q is atypically matched with a pulmonary infarction, similar to PE. Additionally, it possesses the best diagnostic precision.

Magnetic resonance imaging

By using parallel imaging for angiography procedures and pulmonary perfusion, MRI accuracy is continuously improving. This supports its usage along with other possible benefits of MRI, such as a radiation-free approach and a higher safety profile of MR contrast medium.[63]

The comparative standard for investigations utilized a standard pulmonary angiography in a meta-analysis of research that used gadolinium-enhanced MR for imaging acute PE. Sensitivity values from 77% to 100% were recorded, and specificities ranged from 95% to 98%.[7] Other meta-analyses found that the central and lobar arteries had 100% sensitivity for PE, the segmental arteries had 84% sensitivity, whereas the subsegmental portions had only 40% sensitivity.[64]

The PIOPED III trial demonstrated that although 52% of patients (194 of 370) had technically subpar outcomes, technically appropriate MR angiography and venography had a sensitivity of 92% and a specificity of 96%. It was recommended that only individuals for whom comprehensive tests were contraindicated should be examined for MR pulmonary angiography, and only at centers where it is frequently performed well.[65] The most accurate method for determining PE, MR perfusion of the lung, was not used in this investigation, which posed a serious drawback.[66] Gadolinium-based contrast agents have not been shown to be safe in pregnant patients, and unaugmented MRI techniques still need to be improved to accurately assess only the central and first-order artery branches.[67]

Conclusion

The development of diagnostic techniques during the last few years did not reduce the requirement for intrusive diagnostic testing. The existing algorithms rely on the consecutive use of the D-dimer measure, pretest probability evaluation, and, if necessary, a chest imaging examination. These methods are rather easy to understand, practical, and economical. Although these diagnostic approaches have received extensive validation, more work must be done to promote their use and integration into routine clinical practice. It is still difficult to diagnose PE in some patient populations, such as expectant mothers and those with suspected PE recurrence. The concern of overdiagnosis and overtreatment, particularly regarding sub-segmental PE, as well as the lowered clinical suspicion threshold that leads to a lower fraction of PE in suspected patients, are further challenges that may necessitate revisions of present diagnostic approaches. Some of these difficulties might be resolved with the introduction of new diagnostic techniques or improved risk stratification processes.

References

1. Lavorini F, Di Bello V, De Rimini ML, Lucignani G, Marconi L, Palareti G, et al. Diagnosis and treatment of pulmonary embolism: a multidisciplinary approach. Multidiscip Respir Med. 2013 Dec 19;8(1):75. doi: 10.1186/2049-6958-8-75.
2. Tarbox AK, Swaroop M. Pulmonary embolism. Int J Crit Illn Inj Sci. 2013 Jan;3(1):69-72. doi: 10.4103/2229-5151.109427.
3. Nachman D, Pollack A, Herzog E. Epidemiology, Pathophysiology and Predisposing Factors of Pulmonary Embolism and Deep Vein Thrombosis. In: Herzog, E. (eds) Pulmonary Embolism. Springer, Cham; 2022. doi: 10.1007/978-3-030-87090-4_2
4. Anderson DR, Kahn SR, Rodger MA, Kovacs MJ, Morris T, Hirsch A, et al. Computed tomographic pulmonary angiography vs ventilation-perfusion lung scanning in patients with suspected pulmonary embolism: a randomized controlled trial. JAMA. 2007 Dec 19;298(23):2743-53. doi: 10.1001/jama.298.23.2743.
5. Carrier M, Le Gal G, Wells PS, Rodger MA. Systematic review: case-fatality rates of recurrent venous thromboembolism and major bleeding events among patients treated for venous thromboembolism. Ann Intern Med. 2010 May 4;152(9):578-89. doi: 10.7326/0003-4819-152-9-201005040-00008.
6. Okada M, Kunihiro Y, Nakashima Y, Nomura T, Kudomi S, Yonezawa T, Suga K, Matsunaga N. Added value of lung

perfused blood volume images using dual-energy CT for assessment of acute pulmonary embolism. Eur J Radiol. 2015 Jan;84(1):172-177. doi: 10.1016/j.ejrad.2014.09.009.
7. Raymakers AJ, Mayo J, Marra CA, FitzGerald M. Diagnostic strategies incorporating computed tomography angiography for pulmonary embolism: a systematic review of cost-effectiveness analyses. J Thorac Imaging. 2014 Jul;29(4):209-16. doi: 10.1097/RTI.0b013e3182999e41.
8. Beckman MG, Hooper WC, Critchley SE, Ortel TL. Venous thromboembolism: a public health concern. Am J Prev Med. 2010 Apr;38(4 Suppl):S495-501. doi: 10.1016/j.amepre.2009.12.017.
9. Goldhaber SZ, Bounameaux H. Pulmonary embolism and deep vein thrombosis. Lancet. 2012 May 12;379(9828):1835-46. doi: 10.1016/S0140-6736(11)61904-1.
10. Yang S, Yang Y, Zhai Z, Kuang T, Gong J, Zhang S, et al. Incidence and risk factors of chronic thromboembolic pulmonary hypertension in patients after acute pulmonary embolism. J Thorac Dis. 2015 Nov;7(11):1927-38. doi: 10.3978/j.issn.2072-1439.2015.11.43.
11. Naess IA, Christiansen SC, Romundstad P, Cannegieter SC, Rosendaal FR, Hammerstrøm J. Incidence and mortality of venous thrombosis: a population-based study. J Thromb Haemost. 2007 Apr;5(4):692-9. doi: 10.1111/j.1538-7836.2007.02450.x.
12. DeMonaco NA, Dang Q, Kapoor WN, Ragni MV. Pulmonary embolism incidence is increasing with use of spiral computed tomography. Am J Med. 2008 Jul;121(7):611-7. doi: 10.1016/j.amjmed.2008.02.035.
13. Previtali E, Bucciarelli P, Passamonti SM, Martinelli I. Risk factors for venous and arterial thrombosis. Blood Transfus. 2011 Apr;9(2):120-38. doi: 10.2450/2010.0066-10.
14. Zhan ZQ, Wang CQ, Nikus KC, He CR, Wang J, Mao S, Dong XJ. Electrocardiogram patterns during hemodynamic instability in patients with acute pulmonary embolism. Ann Noninvasive Electrocardiol. 2014 Nov;19(6):543-51. doi: 10.1111/anec.12163.
15. Gruettner J, Walter T, Lang S, Meyer M, Apfaltrer P, Henzler T, Viergutz T. Importance of Wells score and Geneva score for the evaluation of patients suspected of pulmonary embolism. In Vivo. 2015 Mar-Apr;29(2):269-72.
16. Lobo SA, Fischer S. Cardiac Risk Assessment. 2022 Jul 25. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan–. PMID: 30725831.
17. van Belle A, Büller HR, Huisman MV, Huisman PM, Kaasjager K, Kamphuisen PW, et al.; Christopher Study Investigators. Effectiveness of managing suspected pulmonary embolism using an algorithm combining clinical probability, D-dimer testing, and computed tomography. JAMA. 2006 Jan 11;295(2):172-9. doi: 10.1001/jama.295.2.172.
18. Moore AJE, Wachsmann J, Chamarthy MR, Panjikaran L, Tanabe Y, Rajiah P. Imaging of acute pulmonary embolism: an update. Cardiovasc Diagn Ther. 2018 Jun;8(3):225-243. doi: 10.21037/cdt.2017.12.01.
19. Mirza H, Hashmi MF. Lung Ventilation Perfusion Scan (VQ Scan). 2022 Oct 17. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan–. PMID: 33232086.
20. Salaun PY, Couturaud F, Le Duc-Pennec A, Lacut K, Le Roux PY, Guillo P, Pennec et al. Noninvasive diagnosis of pulmonary embolism. Chest. 2011 Jun;139(6):1294-1298. doi: 10.1378/chest.10-1209.
21. Lang I. Chronic thromboembolic pulmonary hypertension: a distinct disease entity. Eur Respir Rev. 2015 Jun;24(136):246-52. doi: 10.1183/16000617.00001115.
22. Wiener RS, Schwartz LM, Woloshin S. Time trends in pulmonary embolism in the United States: evidence of overdiagnosis. Arch Intern Med. 2011 May 9;171(9):831-7. doi: 10.1001/archinternmed.2011.178.
23. Le Roux PY, Robin P, Salaun PY. New developments and future challenges of nuclear medicine and molecular imaging for pulmonary embolism. Thromb Res. 2018 Mar;163:236-241. doi: 10.1016/j.thromres.2017.06.031.
24. Jany B, Welte T. Pleural Effusion in Adults-Etiology, Diagnosis, and Treatment. Dtsch Arztebl Int. 2019 May 24;116(21):377-386. doi: 10.3238/arztebl.2019.0377.
25. Moore AJE, Wachsmann J, Chamarthy MR, Panjikaran L, Tanabe Y, Rajiah P. Imaging of acute pulmonary embolism: an update. Cardiovasc Diagn Ther. 2018 Jun;8(3):225-243. doi: 10.21037/cdt.2017.12.01.
26. Stein PD, Fowler SE, Goodman LR, Gottschalk A, Hales CA, Hull RD, et al.; PIOPED II Investigators. Multidetector computed tomography for acute pulmonary embolism. N Engl J Med. 2006 Jun 1;354(22):2317-27. doi: 10.1056/NEJMoa052367.
27. Berdahl CT, Vermeulen MJ, Larson DB, Schull MJ. Emergency department computed tomography utilization in the United States and Canada. Ann Emerg Med. 2013 Nov;62(5):486-494.e3. doi: 10.1016/j.annemergmed.2013.02.018.
28. Hassan HGEMA, Khater NH, Elia RZ. Added value of hyperdense lumen sign in prediction of acute central and peripheral pulmonary embolism on non-contrast CT chest. Egypt J Radiol Nucl Med. 2021;52(1):84. doi: 10.1186/s43055-021-00462-9.
29. Woo JK, Chiu RY, Thakur Y, Mayo JR. Risk-benefit analysis of pulmonary CT angiography in patients with suspected pulmonary embolus. AJR Am J Roentgenol. 2012 Jun;198(6):1332-9. doi: 10.2214/AJR.10.6329. Erratum in: AJR Am J Roentgenol. 2013 Oct;201(4):935.
30. Luk L, Steinman J, Newhouse JH. Intravenous Contrast-Induced Nephropathy-The Rise and Fall of a Threatening Idea. Adv Chronic Kidney Dis. 2017 May;24(3):169-175. doi: 10.1053/j.ackd.2017.03.001.
31. Heller M, Krieger P, Finefrock D, Nguyen T, Akhtar S. Contrast CT Scans in the Emergency Department Do Not Increase Risk of Adverse Renal Outcomes. West J Emerg Med. 2016 Jul;17(4):404-8. doi: 10.5811/westjem.2016.4.28994.
32. Beckett KR, Moriarity AK, Langer JM. Safe Use of Contrast Media: What the Radiologist Needs to Know. Radiographics. 2015 Oct;35(6):1738-50. doi: 10.1148/rg.2015150033.
33. Li X, Chen J, Zhang L, Liu H, Wang S, Chen X, et al. Clinical observation of the adverse drug reactions caused by non-ionic iodinated contrast media: results from 109,255 cases who underwent enhanced CT examination in Chongqing, China. Br J Radiol. 2015 Mar;88(1047):20140491. doi: 10.1259/bjr.20140491.
34. Sohoni CA. Peripheral wedge-shaped radiographic lung opacity in a young patient. Lung India. 2015 Mar-Apr;32(2):184-5. doi: 10.4103/0970-2113.152651.
35. Nishiyama KH, Saboo SS, Tanabe Y, Jasinowodolinski D, Landay MJ, Kay FU. Chronic pulmonary embolism: diagnosis. Cardiovasc Diagn Ther. 2018 Jun;8(3):253-271.
36. Moore AJE, Wachsmann J, Chamarthy MR, Panjikaran L, Tanabe Y, Rajiah P. Imaging of acute pulmonary embolism: an update. Cardiovasc Diagn Ther. 2018 Jun;8(3):225-243. doi: 10.21037/cdt.2017.12.01.
37. Im DJ, Hur J, Han KH, Lee HJ, Kim YJ, Kwon W, Choi BW. Acute Pulmonary Embolism: Retrospective Cohort Study of the Predictive Value of Perfusion Defect Volume Measured With Dual-Energy CT. AJR Am J Roentgenol. 2017 Nov;209(5):1015-1022. doi: 10.2214/AJR.17.17815.
38. Qanadli SD, El Hajjam M, Vieillard-Baron A, Joseph T, Mesurolle B, Oliva VL, et al. New CT index to quantify arterial obstruction in pulmonary embolism: comparison with angiographic index and echocardiography. AJR Am J Roentgenol. 2001 Jun;176(6):1415-20. doi: 10.2214/ajr.176.6.1761415.
39. Mastora I, Remy-Jardin M, Masson P, Galland E, Delannoy V, Bauchart JJ, Remy J. Severity of acute pulmonary embolism: evaluation of a new spiral CT angiographic score in correlation with echocardiographic data. Eur Radiol. 2003 Jan;13(1):29-35.

40. Furlan A, Aghayev A, Chang CC, Patil A, Jeon KN, Park B, et al. Short-term mortality in acute pulmonary embolism: clot burden and signs of right heart dysfunction at CT pulmonary angiography. Radiology. 2012 Oct;265(1):283-93. doi: 10.1148/radiol.12110802.
41. Yu T, Yuan M, Zhang Q, Shi H, Wang D. Evaluation of computed tomography obstruction index in guiding therapeutic decisions and monitoring percutanous catheter fragmentation in massive pulmonary embolism. J Biomed Res. 2011 Nov;25(6):431-7. doi: 10.1016/S1674-8301(11)60057-2.
42. Kubo T, Lin PJ, Stiller W, Takahashi M, Kauczor HU, Ohno Y, Hatabu H. Radiation dose reduction in chest CT: a review. AJR Am J Roentgenol. 2008 Feb;190(2):335-43. doi: 10.2214/AJR.07.2556.
43. Mayo J, Thakur Y. Pulmonary CT angiography as first-line imaging for PE: image quality and radiation dose considerations. AJR Am J Roentgenol. 2013 Mar;200(3):522-8. doi: 10.2214/AJR.12.9928.
44. Ridge CA, Litmanovich D, Bukoye BA, Lin PJ, Wilcox C, Boiselle PM, Bankier AA. Computed tomography angiography for suspected pulmonary embolism: comparison of 2 adaptive statistical iterative reconstruction blends to filtered back-projection alone. J Comput Assist Tomogr. 2013 Sep-Oct;37(5):712-7. doi: 10.1097/RCT.0b013e31829727d2.
45. Pontana F, Henry S, Duhamel A, Faivre JB, Tacelli N, Pagniez J, et al. Impact of iterative reconstruction on the diagnosis of acute pulmonary embolism (PE) on reduced-dose chest CT angiograms. Eur Radiol. 2015 Apr;25(4):1182-9. doi: 10.1007/s00330-014-3393-5.
46. Bogot NR, Fingerle A, Shaham D, Nissenbaum I, Sosna J. Image quality of low-energy pulmonary CT angiography: comparison with standard CT. AJR Am J Roentgenol. 2011 Aug;197(2):W273-8. doi: 10.2214/AJR.10.5318.
47. Schueller-Weidekamm C, Schaefer-Prokop CM, Weber M, Herold CJ, Prokop M. CT angiography of pulmonary arteries to detect pulmonary embolism: improvement of vascular enhancement with low kilovoltage settings. Radiology. 2006 Dec;241(3):899-907. doi: 10.1148/radiol.2413040128.
48. Petersilka M, Bruder H, Krauss B, Stierstorfer K, Flohr TG. Technical principles of dual source CT. Eur J Radiol. 2008 Dec;68(3):362-8. doi: 10.1016/j.ejrad.2008.08.013.
49. Kerl JM, Lehnert T, Schell B, Bodelle B, Beeres M, Jacobi V, Vogl TJ, Bauer RW. Intravenous contrast material administration at high-pitch dual-source CT pulmonary angiography: test bolus versus bolus-tracking technique. Eur J Radiol. 2012 Oct;81(10):2887-91. doi: 10.1016/j.ejrad.2011.09.018.
50. Bauer RW, Schell B, Beeres M, Wichmann JL, Bodelle B, Vogl TJ, Kerl JM. High-pitch dual-source computed tomography pulmonary angiography in freely breathing patients. J Thorac Imaging. 2012 Nov;27(6):376-81. doi: 10.1097/RTI.0b013e318250067e.
51. Hou DJ, Tso DK, Davison C, Inacio J, Louis LJ, Nicolaou S, Reimann AJ. Clinical utility of ultra high pitch dual source thoracic CT imaging of acute pulmonary embolism in the emergency department: are we one step closer towards a non-gated triple rule out? Eur J Radiol. 2013 Oct;82(10):1793-8. doi: 10.1016/j.ejrad.2013.05.003.
52. Bucher AM, Kerl MJ, Albrecht MH, Beeres M, Ackermann H, Wichmann JL, et al. Systematic Comparison of Reduced Tube Current Protocols for High-pitch and Standard-pitch Pulmonary CT Angiography in a Large Single-center Population. Acad Radiol. 2016 May;23(5):619-27. doi: 10.1016/j.acra.2016.01.003.
53. Lu GM, Luo S, Meinel FG, McQuiston AD, Zhou CS, Kong X, et al. High-pitch computed tomography pulmonary angiography with iterative reconstruction at 80 kVp and 20 mL contrast agent volume. Eur Radiol. 2014 Dec;24(12):3260-8.
54. Martini K, Meier A, Higashigaito K, Saltybaeva N, Alkadhi H, Frauenfelder T. Prospective Randomized Comparison of High-pitch CT at 80 kVp Under Free Breathing with Standard-pitch CT at 100 kVp Under Breath-Hold for Detection of Pulmonary Embolism. Acad Radiol. 2016 Nov;23(11):1335-1341.
55. Meinel FG, Canstein C, Schoepf UJ, Sedlmaier M, Schmidt B, Harris BS, et al. Image quality and radiation dose of low tube voltage 3rd generation dual-source coronary CT angiography in obese patients: a phantom study. Eur Radiol. 2014 Jul;24(7):1643-50. doi: 10.1007/s00330-014-3194-x.
56. Parker JA, Coleman RE, Grady E, Royal HD, Siegel BA, Stabin MG, et al.; Society of Nuclear Medicine. SNM practice guideline for lung scintigraphy 4.0. J Nucl Med Technol. 2012 Mar;40(1):57-65. doi: 10.2967/jnmt.111.101386.
57. Roach PJ, Bailey DL, Harris BE. Enhancing lung scintigraphy with single-photon emission computed tomography. Semin Nucl Med. 2008 Nov;38(6):441-9.
58. Dorbala S, Ananthasubramaniam K, Armstrong IS, Chareonthaitawee P, DePuey EG, Einstein AJ, et al. Single Photon Emission Computed Tomography (SPECT) Myocardial Perfusion Imaging Guidelines: Instrumentation, Acquisition, Processing, and Interpretation. J Nucl Cardiol. 2018 Oct;25(5):1784-1846. doi: 10.1007/s12350-018-1283-y.
59. Roach PJ, Schembri GP, Bailey DL. V/Q scanning using SPECT and SPECT/CT. J Nucl Med. 2013 Sep;54(9):1588-96.
60. Leblanc M, Leveillée F, Turcotte E. Prospective evaluation of the negative predictive value of V/Q SPECT using 99mTc-Technegas. Nucl Med Commun. 2007 Aug;28(8):667-72. doi: 10.1097/MNM.0b013e32827a8e99.
61. Yandrapalli S, Puckett Y. SPECT Imaging. 2022 Oct 3. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan–. PMID: 33232084.
62. Bajc M, Neilly JB, Miniati M, Schuemichen C, Meignan M, Jonson B; EANM Committee. EANM guidelines for ventilation/perfusion scintigraphy : Part 1. Pulmonary imaging with ventilation/perfusion single photon emission tomography. Eur J Nucl Med Mol Imaging. 2009 Aug;36(8):1356-70.
63. Hochhegger B, Ley-Zaporozhan J, Marchiori E, Irion K, Souza AS Jr, Moreira J, Kauczor HU, Ley S. Magnetic resonance imaging findings in acute pulmonary embolism. Br J Radiol. 2011 Mar;84(999):282-7. doi: 10.1259/bjr/26121475.
64. Oudkerk M, van Beek EJ, Wielopolski P, van Ooijen PM, Brouwers-Kuyper EM, Bongaerts AH, Berghout A. Comparison of contrast-enhanced magnetic resonance angiography and conventional pulmonary angiography for the diagnosis of pulmonary embolism: a prospective study. Lancet. 2002 May 11;359(9318):1643-7. doi: 10.1016/S0140-6736(02)08596-3.
65. Stein PD, Chenevert TL, Fowler SE, Goodman LR, Gottschalk A, Hales CA, et al.; PIOPED III (Prospective Investigation of Pulmonary Embolism Diagnosis III) Investigators. Gadolinium-enhanced magnetic resonance angiography for pulmonary embolism: a multicenter prospective study (PIOPED III). Ann Intern Med. 2010 Apr 6;152(7):434-43, W142-3. doi: 10.7326/0003-4819-152-7-201004060-00008.
66. Kluge A, Luboldt W, Bachmann G. Acute pulmonary embolism to the subsegmental level: diagnostic accuracy of three MRI techniques compared with 16-MDCT. AJR Am J Roentgenol. 2006 Jul;187(1):W7-14.
67. Pahade JK, Litmanovich D, Pedrosa I, Romero J, Bankier AA, Boiselle PM. Quality initiatives: imaging pregnant patients with suspected pulmonary embolism: what the radiologist needs to know. Radiographics. 2009 May-Jun;29(3):639-54.

***Contact Information:** Assistant Professor, Dr. Zuhal Y. Hamd, PhD. Radiological Sciences Department, College of Health & Rehabilitation Sciences, Princess Nourah Bint Abdulrahman University, P.0. Box 84428, Riyadh 11671, Saudi Arabia. E-mail: zuhalhamd2019@gmail.com*