Received:
11 December 2017

Revised:
08 May 2018

Accepted:
09 May 2018

<https://doi.org/10.1259/bjr.20170956>

Cite this article as:

Cascio V, Hon M, Haramati LB, Gour A, Spiegler P, Bhalla S, et al. Imaging of suspected pulmonary embolism and deep venous thrombosis in obese patients. *Br J Radiol* 2018; **91**: 20170956.

THE ROLE OF IMAGING IN OBESITY SPECIAL FEATURE: REVIEW ARTICLE

Imaging of suspected pulmonary embolism and deep venous thrombosis in obese patients

^{1,2}VINCENT CASCIO, BS, MD, ³MAN HON, MD, ⁴LINDA B HARAMATI, MD, MS, ⁵ANIMESH GOUR, MD, ¹PETER SPIEGLER, MD, ⁶SANJEEV BHALLA, MD and ²DOUGLAS S KATZ, MD, FACR

¹Stony Brook University School of Medicine, Stony Brook, NY, USA

²Department of Radiology, NYU Winthrop, Stony Brook University School of Medicine, Mineola, NY, USA

³Interventional Radiology, NYU Winthrop, Stony Brook University School of Medicine, Stony Brook, NY, USA

⁴Division of Cardiothoracic Imaging, Montefiore Medical Center and the Albert Einstein College of Medicine, Bronx, NY, USA

⁵Division of Pulmonary

and Critical Care Medicine, Department of Internal Medicine, NYU Winthrop, Mineola, NY, USA

⁶Mallinckrodt Institute of Radiology, Washington University School of Medicine, St Louis, MO, USA

Address correspondence to: Dr Douglas S Katz

E-mail: douglas.katz@nyulangone.org

ABSTRACT

Obesity is a growing problem around the world, and radiology departments frequently encounter difficulties related to large patient size. Diagnosis and management of suspected venous thromboembolism, in particular deep venous thrombosis (DVT) and pulmonary embolism (PE), are challenging even in some lean patients, and can become even more complicated in the setting of obesity. Many obstacles must be overcome to obtain imaging examinations in obese patients with suspected PE and/or DVT, and to ensure that these examinations are of sufficient quality to diagnose or exclude thromboembolic disease, or to establish an alternative diagnosis. Equipment limitations and technical issues both need to be acknowledged and addressed. Table weight limits and scanner sizes that readily accommodate obese and even morbidly obese patients are not in place at many clinical sites. There are also issues with image quality, which can be substantially compromised. We discuss current understanding of the effects of patient size on imaging in general and, more specifically, on the imaging modalities used for the diagnosis and treatment of DVT and PE. Emphasis will be placed on the technical parameters and protocol nuances, including contrast dosing, which are necessary to refine and optimize images for the diagnosis of DVT and PE in obese patients, while remaining cognizant of radiation exposure. More research is necessary to develop consistent high-level evidence regarding protocols to guide radiologists, and to help them effectively utilize emerging technology.

INTRODUCTION

The prevalence of obesity around the world is higher than ever; approximately 48% of Europeans are currently overweight or obese, including 56% of people living in England, according to the body mass index (BMI).¹ The situation is even worse in the U.S., as 61% of Americans are overweight, and 37% are obese.^{2,3} Although the increasing prevalence of obesity seems to have slowed in very recent years, the prevalence of morbid obesity is predicted to rise as much as 130% in the next 20 years, according to some estimates.^{3,4} BMI is defined as the body mass in kilograms divided by the square of the body height in meters, and it is the accepted measure used to define obesity according to the World Health Organization and the U.S. National Institute of Health. A BMI of 18.5 to 25 is defined as normal weight, 25 to 30 as overweight and over 30 as obese.⁵ For

the purposes of this review, patient size will be referenced in BMI or weight in kilograms.

Healthcare systems are dealing with numerous issues related to obesity, resulting from patient size and co-morbid conditions, including diabetes, heart disease, orthopedic injuries and sleep apnea. Radiology departments are caring for more overweight and obese patients who require imaging for both acute and chronic conditions, including known or suspected venous thromboembolism (VTE).⁶ VTE includes deep venous thrombosis (DVT) and pulmonary embolism (PE), and occurs at a rate of approximately 100 per 100,000 person-years.⁷ PE is a potentially dangerous condition with a mortality rate between 5–30%, and is responsible for an estimated greater than 290,000 deaths in the U.S. each year.^{8,9}

Overweight and obese patients will continue to present challenges for radiology departments worldwide. Patient size often prevents the proper imaging examination from being performed, or leads to examinations of insufficient quality to be clinically useful. Uppot *et al* retrospectively examined the imaging reports at the Massachusetts General Hospital for the phrase “limited due to body habitus,” and found an increasing rate over time, which was correlated with the increasing prevalence of obesity over an 11-year period between 1991–2001.¹⁰ This is highly relevant when DVT or PE is a diagnostic consideration in obese patients, who are at increased risk for thromboembolic disease.^{11–14} Overcoming the challenges associated with obesity to obtain good imaging is essential for the timely and accurate diagnosis of these patients. This review will discuss the effects of patient size on imaging in general, and on imaging modalities utilized for the diagnosis and treatment of DVT and PE. It will also discuss how to approach the diagnosis of DVT and PE in obese patients, and techniques to optimize imaging examinations in this setting.

DVT/PE IN RELATION TO OBESITY

Obesity is a known risk factor for thromboembolic disease, including PE and DVT. Other risk factors include immobilization, pregnancy and recent surgery. Obesity increases the risk of venous thrombosis by a factor of between 2 and 3, and the risk is greater with morbid obesity.¹¹ Obese females, as well as females taking oral contraceptive pills, are at increased risk of PE, compared to obese males.^{6,15} The rate of DVT and PE following bariatric surgery has been estimated at 1.3 and 0.9%, respectively.¹⁶ The relative risk for PE among obese patients is greatest for young adults and teenagers, with a relative risk of 5.80 *vs* 2.03 across all age groups. The relative risk of PE among obese patients likely lessens with age because the increased prevalence of other co-morbid conditions means that obesity has less of an impact. Obese patients have a lower mortality resulting from PE, and this paradox is even more pronounced in females,¹² for unknown reasons, to our knowledge.

PE usually occurs after the embolization of DVT from the deep veins of the thighs and/or calves, although embolization can occur from clots in the pelvic veins, as well as from the upper extremities, and from the right heart. Most DVT start in the calves, forming around the leaflets of the valves.^{17,18} Virchow's original triad of DVT was stasis, hypercoagulability and trauma to the venous wall, which is still relevant today. Contributing factors in obesity include molecular changes, which increases hypercoagulability; decreased venous flow in the lower extremities, which promotes stasis; and chronic inflammation, which damages the endothelium. Decreased fibrinolytic activity and increased leptin, Von Willebrand factor, factor VII and VIII and estrogen and progesterone activity also may play a role in thromboembolic disease in obese patients.^{6,13,14,18,19}

Accurate diagnosis of DVT and PE is notoriously difficult from a clinical perspective. Both DVT and PE are even more difficult to accurately diagnose non-radiologically in obese patients, because obese patients are more likely to have dyspnea, tachypnea, tachycardia, hypoxemia, leg edema/skin changes and cellulitis, which are not necessarily related to pulmonary venous

thromboembolism.^{20,21} D-dimer levels are also higher in obese patients at baseline, which can complicate the diagnosis.⁶ Because of this, when evaluating the obese patient, it is important to note any acute worsening of these signs or symptoms, if they were previously present.

CHALLENGES OF IMAGING IN OBESITY

Obese patients often cannot receive proper imaging examinations, or receive examinations of insufficient quality, and equipment limitations are one factor contributing to this. Imaging table weight limits can be an obstacle for morbidly obese patients undergoing CT. A 2008 study found that 10% of Irish patients seeking treatment for obesity weighed over 160 kilograms, and were thus approaching the weight limits of the available CT scanners. Up to 5% of patients were too large to receive any cross-sectional imaging.²² A similar study in 2008 found that of U.S. hospitals with emergency departments, only 10% had large weight-capacity CT, and only 8% had large weight-capacity MRI.²³ It is unclear to our knowledge if these statistics are currently improved. However, the current generation of CT scanners can generally accommodate patient weights of approximately 200–300 kilograms, so most obese patients are instead limited by the gantry diameter. Gantry diameter is typically 70 cm in the horizontal dimension, but is usually 15–18 cm narrower in the vertical dimension, after accounting for table thickness.²⁴

Different techniques have been developed to accommodate obese patients in the CT scanner. For example, patients undergoing a CT of the abdomen/pelvis can go into the scanner feet first, and patients undergoing a head CT can stand behind the scanner, placing their head into the cradle.^{25,26} To our knowledge, there has been no study demonstrating the ability to circumvent this problem of gantry diameter in patients who require imaging of the chest. However, fat distribution varies substantially among obese patients, and some patients with abdominal girth which exceeds the gantry diameter may have a thorax which is still able to fit inside the scanner. There is also a common myth that zoos and veterinary clinics are willing to image obese patients who cannot fit inside human CT and MRI scanners, but in fact most of these facilities have specific policies prohibiting human patients.²³

If the obese patient meets the physical limitations of the scanner, other issues may arise. Patient size often causes an insufficient area to be imaged, and difficulty finding anatomical landmarks under the subcutaneous fat can prevent proper technique and positioning from being used.²⁷ Regarding CT, obese patients often require prolonged imaging time, which can result in motion artifacts and increased exposure time. Technical issues include limited field-of-view (FOV), image cropping, increased noise and overall decreased image quality.^{2,24,27,28} Imaging parameters and protocols need to be optimized on an individual basis, and often the size/girth of the patient is more important than weight or BMI alone.²⁹

Obese patients are often exposed to more ionizing radiation when undergoing CT than non-obese patients, because of increased

exposure time, and because they require higher radiation doses to achieve similar image quality as in thinner patients.^{25,27} However, radiation dose to the intra-abdominal organs does not increase linearly with increased total dose, as much of the radiation is absorbed in the subcutaneous fat. Regardless, it does make sense to limit additional radiation in the obese patient when possible, following the “ALARA” principle.^{29,30} Low-voltage protocols have been proposed to limit ionizing radiation dose in CT examinations, and a variety of studies have investigated these protocols in the chest specifically. Because of the low absorption of photons by the lungs compared to the abdomen, there is less noise, and image quality can be maintained at lower voltages in chest CT and CT pulmonary angiography (CTPA) examinations in patients of normal weight, although not necessarily in obese patients.^{31–33} It is important to be mindful that there is often a trade-off between image quality and radiation dose, especially in obese patients, and to utilize low-dose protocols where appropriate.

CT PULMONARY ANGIOGRAPHY

CTPA is currently the most common imaging modality utilized for patients with suspected PE. It is highly accurate for the diagnosis of PE, with sensitivity and specificity over 94%.³⁴ CTPA is available in emergency departments, can be performed quickly, and can be used to identify as well as exclude many other conditions in the differential diagnosis of PE. Due to its usefulness, the number of CTPAs performed in the U.S. has been steadily increasing in recent years, and as a result the test has recently come under scrutiny for overutilization due to falling diagnostic yield rates. PE was identified in 22.6% of CTPAs in the PIONEER II study, but its incidence has been around 14–18%, and as low as 9%, in more recent studies.^{35–38}

The accuracy of CTPA in overweight and obese patients is generally good (Figure 1). Some studies have shown no difference in subjective image quality, diagnostic confidence, or diagnostic accuracy between obese and non-obese patients.^{39–41} Despite this reassuring data, however, there is evidence that obesity can still be a problem in CTPA examinations. Obesity was noted to be a cause of non-diagnostic CTPA examinations in several studies, and the increasing prevalence of obesity may play a role in the worsening diagnostic yield of CTPA.⁶ CTPA studies on overweight and obese patients show statistically significantly decreased levels of pulmonary artery enhancement, signal-to-noise ratio (SNR), contrast-to-noise (CNR) and subjective image

quality.^{6,42} (Figure 2). In a retrospective study in 2016, Yeo et al found that 6% of 403 total CTPAs were indeterminate, with 23 suboptimal examinations, and 1 non-diagnostic examination. Higher weight was a predictor of an indeterminate examination. Of 24 indeterminate examinations, 3 were specifically attributed to body habitus, due to quantum mottle causing excess noise. Other causes of indeterminate examinations included suboptimal pulmonary enhancement, motion artifacts and lower lobe pneumonia, which decreased accuracy.⁹

quality.^{6,42} (Figure 2). In a retrospective study in 2016, Yeo et al found that 6% of 403 total CTPAs were indeterminate, with 23 suboptimal examinations, and 1 non-diagnostic examination. Higher weight was a predictor of an indeterminate examination. Of 24 indeterminate examinations, 3 were specifically attributed to body habitus, due to quantum mottle causing excess noise. Other causes of indeterminate examinations included suboptimal pulmonary enhancement, motion artifacts and lower lobe pneumonia, which decreased accuracy.⁹

FIELD OF VIEW

CTPA examinations of obese patients are affected by the same general imaging limitations discussed above. Some obese patients exceed table weight limits or cannot fit into the gantry, although new scanners with larger weight limits can alleviate some of these issues.^{6,24,29} Of note, the FOV is typically smaller than the gantry of a CT scanner. For example, a 70 cm gantry only has a 55–65 cm FOV, and if any part of the patient is outside that FOV, it can manifest as a beam-hardening or truncation artifact (Figure 1).

Beam and truncation artifacts occur because the CT computer assumes that all attenuation comes from within the FOV, so tissue outside this area can cause the periphery of an obese patient to appear dense. Adjusting the obese patient so that the area in question lies inside the FOV may be helpful, and wrapping obese

Figure 1. CT pulmonary angiography in a 15-year-old boy with a BMI of 50. Although the patient is obese, and there is truncation artifact on the left side, the examination is diagnostic for saddle PE (arrows in a, b) and associated right heart strain (c). BMI, body mass index; PE, pulmonary embolism.

patients in sheets can reduce artifacts, by making the distribution of fat more symmetric.^{24,29} If part of the patient must remain outside the FOV, reconstruction techniques can be used, including FOV extrapolation and truncation artifact correction, which are supported by many current CT scanners.²⁹

TUBE VOLTAGE (KV)

Noise on CT is inversely proportional to the square root of the number of photons used to create the image, and thus noise is the result of poor penetration.⁴³ Photon attenuation decreases the CNR, and since photon attenuation is worsened in the setting of obesity, dose will need to be increased to prevent increased noise, when imaging obese patients. Noise is amplified by low (80–100 kVp) peak tube voltage, as it decreases the average energy spectrum of the emitted photons, which causes poor penetration of the tissue.⁴³ Noise can be reduced in the obese patient by increasing kVp as high as 140, but multiple studies have shown that 120 kVp is sufficient for the overwhelming majority of obese patients^{9,24,29} (Figure 3). Despite reduced CNR, CTPA can be used at 100 kVp in patients weighing up to 125 kg, with no decrease in subjective image quality or diagnostic confidence, and 80 kVp is sufficient for patients weighing up to 100 kg.^{40,41}

A main cause of indeterminate CTPA is limited i.v. contrast enhancement of the pulmonary arteries, and subjective image quality is more closely related to vessel enhancement than to noise.^{9,36,41} There is a statistically significant negative correlation reported between mean/peak vessel enhancement and patient size.^{41,42} Lowering the kVp can increase HU in the pulmonary arteries, making them appear brighter, because the attenuation of the beam increases as the beam energy reaches the k-edge of iodine. Also, less contrast can be used, and radiation dose can be reduced compared to examinations using higher kVp.^{36,43,44} Lowering kVp will cause noise in vessels to increase, but subjective image quality will stay the same because SNR of the vascular structures will increase. However, in obese patients it is not always possible to lower the kVp, because at low kVp the current required for a diagnostic scan may exceed the tube capacity, which would necessitate prolonging the scan, to achieve adequate mAs. New scanners, particularly dual-source CT scanners, may be helpful in solving these problems.³⁶

TUBE CURRENT (MA) AND PITCH

Besides low tube voltage, noise is also amplified on CT by low power generator tube systems, and a fast rotation time (0.4–0.6 s).⁴³ In obese patients, it may be useful to increase the tube current, so that an adequate number of photons are generated. Increasing mAs will decrease noise, but it comes at the “cost” of increasing radiation dose to the patient, and can be constrained by the heating and power generation limits of the CT scanner.^{24,43,45} Software exists which can automatically adjust kVp and mA according to body habitus at specific levels during the scan. Automatic tube current modulation is a technique which uses automatic adjustment of the tube current according to patient size and attenuation in the region being imaged, and can preserve image quality while reducing radiation.^{24,45}

Figure 3. CT pulmonary angiography in a 39-year-old female with a BMI of 40. An initial scan with a kVp of 100 (a) shows a questionable PE (arrow). Repeat scan with a kVp of 120 (b) shows that this was an artifact. BMI, body mass index; .

Slowing gantry rotation to increase effective mAs can also be beneficial. Setting gantry rotation to “automatic” will allow the CT computer to determine the best speed for each level. Obese patients are more likely to be dyspneic and often require prolonged imaging times to maintain image quality, however, which can lead to motion artifacts. Motion artifact is a major cause of indeterminate CTPA examinations when using a 4 to 16-slice scanner, but this has been improved with a 64-slice scanner, in some reports in the literature.^{9,34,46} In patients who cannot do inspiratory breath holding, shallow free breathing can be effective and does not cause motion artifact, when using dual-source high-pitch CTPA.⁴⁷

Lowering the pitch by using thicker collimation can also decrease photon starvation, and thus improve SNR^{2,25} (Figure 4). Decreasing noise by using a lower pitch comes at the cost of

Figure 4. CT pulmonary angiography in a 17-year-old boy with dyspnea and possible PE. An initial scan with 1 mm thick images (a) shows excessive noise. A repeat scan with 3 mm thick images (b) shows reduced noise.

prolonged imaging time, possibly causing motion artifact, as well as increased radiation dose. Ultimately, optimizing tube current and pitch to obtain adequate imaging in the obese patient requires a balance between radiation exposure and image noise.

CONTRAST DOSE

Blood volume and cardiac output both affect vascular enhancement, and obese patients have higher blood volume, which can dilute i.v. contrast.⁴³ Iodine concentration and delivery rate must be optimized to overcome hemodilution and achieve adequate

Figure 5. CTPA in a 34-year-old male with a BMI of 75. Initial evaluation (a) was markedly limited due to infiltration of i.v. access and the patient's large body habitus. This was a non-diagnostic examination for PE. A new i.v. was placed, and subsequent repeat CTPA (b–d) demonstrated extensive bilateral PE (arrows) with a saddle component, and associated right heart strain. BMI, body mass index; CTPA, CT pulmonary angiography; PE, pulmonary embolism.

vascular enhancement in these patients. Vessel enhancement can be increased by giving more contrast medium, or by giving smaller volumes of high-concentration contrast.^{6,36,48} Pulmonary artery attenuation and overall CTPA quality is optimized by using higher concentrations of iodine (1.6 gI s^{-1}) and rapid delivery.⁴⁹

Administration of i.v. contrast in obese patients may be difficult due to increased soft-tissue thickness, and consequent difficulty placing and maintaining i.v. access (Figure 5). At times, placing an i.v. catheter in obese patients may require ultrasound guidance to locate veins which are neither visible nor palpable. There is also an increased prevalence of venous insufficiency in the obese population. Iodine is ideally given through an 18-gauge peripheral venous catheter, although a 20-gauge fenestrated catheter performs just as well as an 18-gauge non-fenestrated catheter with respect to i.v. contrast infusion rates, and thus may be a better choice in obese patients.⁵⁰

ITERATIVE RECONSTRUCTION

Iterative reconstruction is a relatively new CT technique that allows for radiation dose reduction. This technique uses more complex modeling of noise distribution than standard filtered back projection techniques. Image quality can improve during each iteration, and this produces significantly enhanced overall quality, which can then be combined with radiation dose reduction techniques.⁵¹ Iterative reconstruction has successfully been used in obese patients undergoing CTPA to lower kVp, reduce

Figure 6. Lower extremity ultrasound in a 73-year-old female with a BMI of 63.5. Non-compression (a) and compression (b) views of the right femoral and deep femoral vein shows probable thrombus of the right common femoral vein. Subsequent CTV (c) of the same patient, performed after sonography, confirms right upper thigh DVT (arrow). BMI, body mass index; CTV, CT venography; DVT, deep venous thrombosis.

noise and to lower total radiation dose, without decreasing image resolution or quality.^{36,43,52} Iterative reconstruction is computationally intensive in regard to image reconstruction time, but should be used in obese patients when possible, as it can overcome many of the associated challenges. Some programs allow the user to specify a percentage of iterative reconstruction vs filtered back projection, which may also be time-saving.²⁹

CT VENOGRAPHY

CT venography (CTV) allows for examination of all the veins of the calves, as well as of the iliac veins, inferior vena cava and profunda femoral veins, which are not easily evaluated routinely with ultrasound (Figure 6). CTV has fallen out of favor and the

technique is rarely used alone.¹⁸ Combined CTV and CTPA, a.k.a. CTVPA, however, is useful for identifying DVT in locations more difficult to scan with ultrasound, as well as in the thighs and proximal calf veins.⁵³

The PIOPED II study demonstrated that adding CTV to CTPA had a sensitivity of 90% for the detection of VTE, compared to 83% in CTPA,⁵⁴ although the overall number of additional patients that were identified with VTE with the addition of CTV was relatively small. It may be beneficial to selectively use CTVPA instead of sonography in the obese patient, because the deep veins of the thigh are better visualized with CT, compared with on ultrasound, although in marked obesity the CT images may also be limited. CTVPA can serve as a baseline for future comparison to monitor treatment, and can provide evidence of DVT if there is an otherwise non-diagnostic CTPA examination.⁵³

DUAL-ENERGY CT

Dual-energy CT (DECT), using a dual-source CT scanner, or other technologies including rapid kVp switching with a single-source scanner, allows for the simultaneous acquisition of images using more than one tube voltage, and thus analysis of tissue composition, pixel-by-pixel. The use of an iodine-subtraction technique, for example, allows the generation of “virtual” non-enhanced images, without the need for actual non-enhanced scanning, reducing radiation dose. DECT has multiple applications in PE, including the ability to provide information about ventilation and perfusion, by mapping iodine distribution in the lungs, although routine use of DECT for imaging patients with suspected PE is not in wide use at present, to our knowledge. The ability to visualize perfusion deficits resulting from thromboembolism can affect risk stratification and management decisions.^{55,56}

DECT has some advantages over traditional single-source CT in the diagnosis of PE, particularly in more reliably revealing peripheral PE. One study using DECT found ventilation-perfusion (V/Q) mismatch in 8 out of 10 patients with PE, including one patient with peripheral PE not identified using CTPA. This study excluded patients who did not fit into the smaller FOV of the “B”-tube of the dual-source scanner.⁵⁶ In a study of 15 patients, Thieme *et al* reported both a sensitivity and specificity of 100% for DECT for the diagnosis of acute PE.⁵⁷ Mao *et al* reported that DECT combined with perfusion mapping significantly improved the detection rate of peripheral PE compared to CTPA alone.⁵⁸

Use of DECT in general is unfortunately still somewhat limited in obese patients. Dual source DECT scanners traditionally have a smaller FOV than single-source scanners, which can be a limitation when scanning obese patients, although newer scanners are better in this regard.⁵⁹ Diaphragmatic motion artifacts are also a common pitfall of DECT when interpreting perfusion images, and this may be accentuated in obese patients who cannot hold their breath.⁵⁵ DECT technology is also more sensitive to noise than traditional single-source CT, because the technique relies on separated beam spectra, and the lower voltage X-ray tube introduces noise when imaging larger patients.⁶⁰ Noise interferes

with analysis in these patients, and can cause artifacts including beam-hardening.^{55,60} One way to limit noise in obese patients is to increase the energy of the lower voltage tube from 80 kVp to 100 kVp, and the benefits of this setup may justify the reduced spectral energy separation.⁶¹ However, this alteration is only possible with some vendors, which can pose a limitation.

Iterative reconstruction, when combined with DECT, has been shown to decrease noise and increase accuracy in iodine quantification.^{60,61} The use of tin filtration of the high-energy spectrum has been demonstrated to be helpful by absorbing low-energy photons, and thus reducing the overlap between the spectra of the two tubes. However, image noise and variability in iodine measurements remain problematic in obese patients.⁶¹ The use of virtual monoenergetic images at low kiloelectronvolt levels is a possible method to increase vascular enhancement in DECT examinations. Diagnostic image quality for detecting PE is improved because this technique significantly increases iodine contrast, and this technique may allow for a reduced iodine dose.^{62,63} To our knowledge, there is no data on how obesity affects the accuracy of DECT in the diagnosis of PE specifically. Therefore, how different acquisition and reconstruction techniques affect PE diagnosis remains unknown, to our knowledge.

ULTRASOUND

Ultrasound is the imaging examination of choice for suspected DVT. Ultrasound uses no ionizing radiation, and can be performed quickly, without any need for transporting the patient, if done portably.¹⁸ Compression ultrasonography is used, in which the operator presses on the vein using the transducer, starting in the proximal deep venous system and moving distally. If the vein collapses there is presumed to be no DVT, but if the vein does not collapse the examination is essentially diagnostic of DVT. As the majority of PE embolize from the deep veins of the upper thighs and calves, ultrasound has some clinical utility in PE and in monitoring the presence or absence, as well as the progression of, venous thromboembolism.^{6,18}

Unfortunately, in general, ultrasound is the imaging modality which is most likely to be affected by obesity.^{6,27} Parts of the proximal deep venous system can be difficult to visualize and compress, especially the pelvic veins, as well as veins inside the adductor canal, because of their deep course. These difficulties may be amplified in obese patients, due to increased soft-tissue thickness overlying the anatomy (Figure 7). The most common sites of DVT are the common femoral and popliteal veins, which are located relatively superficially, and which are therefore better-visualized in most obese patients.^{6,64} Venous compression can be challenging even in superficial veins, which is a limitation of ultrasound in obese patients, and a potential source of false-positive results.

Increased fat causes poor penetration of sound waves into the tissues being imaged, which may result in a limited examination (Figure 8). Sound attenuation through any tissue (dB) is equal to the product of the attenuation coefficient (0.63 dB/cm at 1 MHz for fat), the transducer frequency (MHz), and the thickness of the tissue (cm). Therefore, as transducer frequency or thickness

of subcutaneous fat increases, the attenuation of the sound waves increases.^{24,29} When imaging obese patients, it is important to use low frequency (2 MHz) transducers, to take the subcutaneous fat into account by examining previous imaging, and to position the transducer appropriately (*i.e.* pushing the subcutaneous fat out of the way), which will allow sound waves to reach the area being imaged.^{24,25,29}

Tissue harmonic imaging is based on the distortion of sound waves as they move through certain tissue, and can be beneficial in imaging the obese patient. This technique causes the sound intensity to increase with depth to a point, proportional to the non-linearity coefficient of the tissue.⁶⁵ Fat has the highest non-linearity coefficient, which makes harmonic imaging a valuable tool for penetrating into subcutaneous fat, and for improving the overall image quality of sonography.^{25,29} Harmonic imaging has been shown to improve visualization of the deep venous system during compression examinations, as well as pelvic structures and soft-tissue fluid collections in obese patients.⁶⁶ Image quality can also be improved in obese patients by using tissue aberration correction technology to improve contrast.²⁵

VENTILATION-PERFUSION SCANNING

The role of V/Q scanning has diminished with the increased role of CTPA in diagnosing PE. Nevertheless, the V/Q scan demonstrates excellent performance in stable patients with normal or near-normal chest radiographs.^{67–69} It is the diagnostic test of choice for patients with contraindications to CTPA and for chronic thromboembolic disease, and is useful in differentiating vascular and parenchymal diseases in the lungs. A normal pattern of perfusion is considered sufficient to call PE “unlikely,” with a false-negative rate of only 1.0%.^{70,71} However, an abnormal pattern of perfusion can be complicated by underlying

Figure 8. Ultrasound in a 30-year-old male with a BMI of 68.7. Non-compression longitudinal image of the right femoral vein (a) shows limited visualization of the vein due to overlying soft tissue. The vein is identified by Doppler imaging (b) at a depth of 7 cm. No DVT was identified. Subsequent CTPA shows an embolus in the right lower lobe pulmonary artery (arrow in c), mild cardiomegaly (c) and contrast-blood mixing artifact in the left heart (arrow in d). BMI, body mass index; CTPA, CT pulmonary angiography; DVT, deep venous thrombosis.

cardiopulmonary disease.⁷⁰ The availability of the V/Q scan is limited to weekdays in many institutions and practices, which has contributed to its reduced utilization.

Obesity complicates the performance of V/Q scans, as patients can exceed table weight limits, which are normally 140–200 kilograms, and these patients sometimes cannot fit between the heads of the scanners. In these patients an “upright” V/Q scan, or a scan using a single-head scanner, may need to be utilized.²⁴ Upright V/Q scans are often poor quality, and require reducing the FOV when the patient does not fit into the scanner’s FOV, often resulting in non-diagnostic examinations (Figure 9). Upright imaging poses a risk to patients, because they remain immobile for up to an hour, which is inadvisable in the setting of possible PE.⁶

Weight also degrades image quality in V/Q scans, because increased soft-tissue mass causes photon scatter and decreases SNR.²⁴ Radioisotope dose is calculated based on patient weight, but if the proportionate dose of radioisotope for a patient’s weight exceeds the maximum allowable value, the scan can be compromised, if an inadequate amount of radioisotope is used. When imaging an obese patient, the maximum allowable amount of radioisotope should therefore be used, and the scan should be continued for enough time to obtain necessary images. However, this will not always be possible or sufficient to obtain diagnostic quality images.^{6,24}

Figure 9. Lung V/Q scan in a 26-year-old male with a BMI of 83. Planar ventilation images of the lungs were obtained in the anterior (a), right anterior oblique (b) and left anterior oblique (c) projections. Corresponding planar perfusion images of the lungs were obtained in the anterior (d), right anterior oblique (e) and left anterior oblique (f) projections. Posterior views of the lungs could not be obtained due to the patient’s body habitus. Dedicated gamma camera imaging table for the lung scan could not be utilized, and lung images were only obtained in the anterior views while the patient was in a supine position on his hospital stretcher. Paired ventilation images demonstrate matched ventilation defects, which are larger than the perfusion defects. There are no segmental or subsegmental mismatched perfusion and ventilation abnormalities to suggest pulmonary embolism in the visualized anterior view. BMI, body mass index; V/Q scan, ventilation-perfusion scan.

Some other V/Q techniques have become important in the diagnosis of PE in recent years. Macroaggregated albumin perfusion imaging alone can be useful in patients who cannot undergo a CTPA, including obese patients who exceed table weight limits, cannot fit in the scanner, or cannot hold their breath, or in patients with renal disease and a contraindication to i.v. contrast administration. An abnormal pattern of perfusion should be considered suspicious for PE.⁷²

SPECT V/Q can overcome many of the limitations of planar V/Q scanning by using three-dimensional data, and has become the standard of care outside the U.S.⁷³ In one study, SPECT V/Q reduced indeterminate examinations to fewer than 5%, and has been shown to be superior to planar V/Q imaging in both human and animal studies.^{74–76} However, its use remains very limited in the U.S., because it takes up to 30 min to perform an adequate examination, and it requires technetium-based gases which may not be available. This technique may be beneficial in obese patients, although there is currently no data to support this, to our knowledge.

CONVENTIONAL LOWER EXTREMITY VENOGRAPHY AND PULMONARY ANGIOGRAPHY

Lower extremity venography and pulmonary angiography are not routinely utilized due to the availability of CTPA, which has a higher accuracy for the diagnosis of PE and is less invasive.^{6,72} Conventional venography currently has limited usefulness in the diagnosis of DVT, although it can be helpful very selectively in obese patients with an indeterminate ultrasound, and is, however, relatively frequently used for “road-mapping” in conjunction with inferior vena cava filter placement. It is

also used during the treatment of extensive lower extremity DVT, typically involving the common femoral vein and above, to decrease the incidence of post-thrombotic syndrome, with its associated long-term morbidity.

Conventional venography and angiography can be complicated in obese patients, because they need to be performed on a fluoroscopy table, which have weight limits around 350–500 lbs.^{6,77} Lack of venous access in some obese patients can also prevent these examinations.⁶ Morbidly obese patients have an increased risk of major bleeding from angiography.⁷⁸ To our knowledge, there is no data on the accuracy of conventional venography or angiography for the diagnosis of DVT or PE in obese patients compared to in leaner patients.

INTERVENTIONAL RADIOLOGY TREATMENT OF VTE

Low-risk PE is normally treated with anticoagulation, but there are many different options for the treatment of high-risk PE. The goal for treating more extensive PE is to restore blood flow to the lung tissue, reducing pulmonary hypertension and relieving right heart failure. This can be achieved via systemic thrombolysis, surgical embolectomy, or endovascular interventions. Endovascular treatments for PE include catheter-directed aspiration, fragmentation, local thrombolytic infusion and embolectomy.^{79,80}

Endovascular treatment of PE is usually reserved for when systemic thrombolysis fails, although it can also be used as a more aggressive first-line treatment.⁷⁹ Catheter-directed therapy has been shown to be safe and effective in treating acute PE. In the Pulmonary Embolism Response to Fragmentation, Embolectomy and Catheter Thrombolysis (PERFECT) study, the use of rapid clot debulking was an effective treatment in 85.7% of patients with massive PE, and low-dose, catheter directed local thrombolysis was effective in 97.3% of patients with submassive PE. There were no complications in this study

of 101 patients, and the BMI of the patient population was 37 ± 7 , which is reassuring for physicians treating obese patients.⁸¹

Although the data on PE treatment is limited, to our knowledge, in obese patients, other studies have found a higher risk of complications in obese patients undergoing endovascular procedures. There are many challenges that must be overcome in the obese patient, including equipment limitations, as noted, as patients must fit on relatively narrow fluoroscopy tables with relatively low weight limits and small apertures. Excess subcutaneous tissue can increase the distance a catheter travels, increasing the risk of malposition when the patient moves. Thick tissue can also limit compression and increase the likelihood of access-site bleeding.^{81,82} Obese patients are also at a higher risk for various complications resulting from these procedures.^{82–85} The issues surrounding endovascular treatment of obese patients can be minimized with close management, and relationships with consulting services.

CONCLUSION

As almost half of Europeans and two-thirds of Americans are overweight or obese, and with the prevalence of morbid obesity expected to continue to rise, the U.S., the U.K., and the health-care systems in other countries must adapt to deal with the issues obesity brings. Radiology departments are increasingly asked to image acute and chronic conditions related to obesity, including DVT and PE. Overcoming the challenges associated with obesity to obtain good imaging is essential for the diagnosis of these diseases. For each imaging modality, various technical modifications can be undertaken to ensure that the patient is able to be imaged, and that the imaging result is of sufficient quality to be clinically useful. Specialized transducers, high weight-capacity scanners, reconstruction techniques and modifications in kVp settings can all help to optimize the imaging of DVT/PE in obese patients. Promising new techniques and equipment are becoming available which can help radiology departments confront this issue, although further research on outcomes is necessary.

REFERENCES

- Gallus S, Lugo A, Murisic B, Bosetti C, Boffetta P, La Vecchia C. Overweight and obesity in 16 European countries. *Eur J Nutr* 2015; **54**: 679–89. doi: <https://doi.org/10.1007/s00394-014-0746-4>
- Carucci LR. Imaging obese patients: problems and solutions. *Abdom Imaging* 2013; **38**: 630–46. doi: <https://doi.org/10.1007/s00261-012-9959-2>
- Flegal KM, Kruszon-Moran D, Carroll MD, Fryar CD, Ogden CL. Trends in obesity among adults in the United States, 2005 to 2014. *JAMA* 2016; **315**: 2284–91. doi: <https://doi.org/10.1001/jama.2016.6458>
- Finkelstein EA, Khavjou OA, Thompson H, Trogdon JG, Pan L, Sherry B, et al. Obesity and severe obesity forecasts through 2030. *Am J Prev Med* 2012; **42**: 563–70. doi: <https://doi.org/10.1016/j.amepre.2011.10.026>
- Bmi classification [Internet]. 2007. World Health Organization. cited 11/13/2007.
- Hawley PC, Hawley MP. Difficulties in diagnosing pulmonary embolism in the obese patient: a literature review. *Vasc Med* 2011; **16**: 444–51. doi: <https://doi.org/10.1177/1358863X11422571>
- Wilbur J, Shian B. Diagnosis of deep venous thrombosis and pulmonary embolism. *Am Fam Physician* 2012; **86**: 913–9.
- Heit JA, Cohen AT, Anderson FA. Estimated annual number of incident and recurrent, non-fatal and fatal venous thromboembolism (VTE) events in the US. *Blood* 2005; **106**: 910.
- Yeo JH, Zhou L, Lim R. Indeterminate CT pulmonary angiogram: Why and does it matter? *J Med Imaging Radiat Oncol* 2017; **61**: 18–23. doi: <https://doi.org/10.1111/1754-9485.12500>
- Uppot RN, Sahani DV, Hahn PE, Kalra MK, Saini SS, Mueller PR. Effect of obesity on image quality: fifteen-year longitudinal study for evaluation of dictated radiology reports. *Radiology* 2006; **240**: 435–9. doi: <https://doi.org/10.1148/radiol.2402051110>
- Cushman M. Epidemiology and risk factors for venous thrombosis. *Semin Hematol* 2007; **44**: 62–9. doi: <https://doi.org/10.1053/j.seminhematol.2007.02.004>

12. Stein PD, Matta F, Goldman J. Obesity and pulmonary embolism: the mounting evidence of risk and the mortality paradox. *Thromb Res* 2011; **128**: 518–23. doi: <https://doi.org/10.1016/j.thromres.2011.10.019>
13. Braekkan SK, Siegerink B, Lijfering WM, Hansen JB, Cannegieter SC, Rosendaal FR. Role of obesity in the etiology of deep vein thrombosis and pulmonary embolism: current epidemiological insights. *Semin Thromb Hemost* 2013; **39**: 533–40. doi: <https://doi.org/10.1055/s-0033-1343355>
14. Agnelli G, Becattini C. Acute pulmonary embolism. *N Engl J Med* 2010; **363**: 266–74. doi: <https://doi.org/10.1056/NEJMr0907731>
15. Stein PD, Beemath A, Olson RE. Obesity as a risk factor in venous thromboembolism. *Am J Med* 2005; **118**: 978–80. doi: <https://doi.org/10.1016/j.amjmed.2005.03.012>
16. Stein PD, Matta F. Pulmonary embolism and deep venous thrombosis following bariatric surgery. *Obes Surg* 2013; **23**: 663–8. doi: <https://doi.org/10.1007/s11695-012-0854-2>
17. Stein PD, Hull RD, Saltzman HA, Pineo G. Strategy for diagnosis of patients with suspected acute pulmonary embolism. *Chest* 1993; **103**: 1553–9. doi: <https://doi.org/10.1378/chest.103.5.1553>
18. Katz D, Fruauff K, Kranz A, Hon M. Imaging of deep venous thrombosis: a multimodality overview. *Appl Radiol* 2014; **43**: 6.
19. Vilahur G, Ben-Aicha S, Badimon L. New insights into the role of adipose tissue in thrombosis. *Cardiovasc Res* 2017; **113**: 1046–54. doi: <https://doi.org/10.1093/cvr/cvx086>
20. Hirohashi T, Yoshinaga K, Sakurai T, Kanai M, Shimizu K, Sugiyama Y, et al. Study of the echocardiographic diagnosis of acute pulmonary thromboembolism and risk factors for venous thromboembolism. *J Cardiol* 2006; **47**: 63–71.
21. Yosipovitch G, DeVore A, Dawn A. Obesity and the skin: skin physiology and skin manifestations of obesity. *J Am Acad Dermatol* 2007; **56**: 901–16. doi: <https://doi.org/10.1016/j.jaad.2006.12.004>
22. Campbell N, Buckley O, McGlone B, O'Shea D, Torreggiani WC. Obesity in Ireland in 2008: what radiological equipment is available to image the obese patient? *Ir Med J* 2009; **102**: 116–7.
23. Ginde AA, Foianini A, Renner DM, Valley M, Camargo CA. The challenge of CT and MRI imaging of obese individuals who present to the emergency department. *Obesity* 2008; **16**: 2549–51. doi: <https://doi.org/10.1038/oby.2008.410>
24. Uppot RN, Sahani DV, Hahn PF, Gervais D, Mueller PR. Impact of obesity on medical imaging and image-guided intervention. *AJR Am J Roentgenol* 2007; **188**: 433–40. doi: <https://doi.org/10.2214/AJR.06.0409>
25. Buckley O, Ward E, Ryan A, Colin W, Snow A, Torreggiani WC. European obesity and the radiology department. What can we do to help? *Eur Radiol* 2009; **19**: 298–309. doi: <https://doi.org/10.1007/s00330-008-1154-z>
26. Goldsmith P, Patel A, Farmer R, Wright G, Brown J. A novel technique for CT imaging the brain of the obese patient. *Clin Radiol* 2008; **63**: 575–6. doi: <https://doi.org/10.1016/j.crad.2007.05.030>
27. Le NT, Robinson J, Lewis SJ. Obese patients and radiography literature: what do we know about a big issue? *J Med Radiat Sci* 2015; **62**: 132–41. doi: <https://doi.org/10.1002/jmrs.105>
28. Reynolds A. Obesity and medical imaging challenges. *Radiol Technol* 2011; **82**: 219–39.
29. Modica MJ, Kanal KM, Gunn ML. The obese emergency patient: imaging challenges and solutions. *Radiographics* 2011; **31**: 811–23. doi: <https://doi.org/10.1148/rg.313105138>
30. Yanch JC, Behrman RH, Hendricks MJ, McCall JH. Increased radiation dose to overweight and obese patients from radiographic examinations. *Radiology* 2009; **252**: 128–39. doi: <https://doi.org/10.1148/radiol.2521080141>
31. Sigal-Cinqualbre AB, Hennequin R, Abada HT, Chen X, Paul JF. Low-kilovoltage multi-detector row chest CT in adults: feasibility and effect on image quality and iodine dose. *Radiology* 2004; **231**: 169–74. doi: <https://doi.org/10.1148/radiol.2311030191>
32. Kim MJ, Park CH, Choi SJ, Hwang KH, Kim HS. Multidetector computed tomography chest examinations with low-kilovoltage protocols in adults: effect on image quality and radiation dose. *J Comput Assist Tomogr* 2009; **33**: 416–21. doi: <https://doi.org/10.1097/RCT.0b013e318181fab5>
33. Chen EL, Ross JA, Grant C, Wilbur A, Mehta N, Hart E, et al. Improved image quality of low-dose CT pulmonary angiograms. *J Am Coll Radiol* 2017; **14**: 648–53. doi: <https://doi.org/10.1016/j.jacr.2016.11.007>
34. Jones SE, Wittram C. The indeterminate CT pulmonary angiogram: imaging characteristics and patient clinical outcome. *Radiology* 2005; **237**: 329–37. doi: <https://doi.org/10.1148/radiol.2371041520>
35. Gottschalk A, Stein PD, Goodman LR, Sostman HD. Overview of prospective investigation of pulmonary embolism diagnosis II. *Semin Nucl Med* 2002; **32**: 173–82. doi: <https://doi.org/10.1053/snuc.2002.124177>
36. Devaraj A, Sayer C, Sheard S, Grubnic S, Nair A, Vlahos I. Diagnosing acute pulmonary embolism with computed tomography: imaging update. *J Thorac Imaging* 2015; **30**: 176–92. doi: <https://doi.org/10.1097/RTI.0000000000000146>
37. Mountain D, Keijzers G, Chu K, Joseph A, Read C, Blecher G, et al. RESPECT-ED: rates of pulmonary emboli (PE) and sub-segmental PE with modern computed tomographic pulmonary angiograms in emergency departments: a multi-center observational study finds significant yield variation, uncorrelated with use or small PE rates. *PLoS One* 2016; **11**: e0166483. doi: <https://doi.org/10.1371/journal.pone.0166483>
38. Costa AF, Basseri H, Sheikh A, Stiell I, Dennie C. The yield of CT pulmonary angiograms to exclude acute pulmonary embolism. *Emerg Radiol* 2014; **21**: 133–41. doi: <https://doi.org/10.1007/s10140-013-1169-x>
39. Megyeri B, Christe A, Schindera ST, Horkay E, Sikula J, Cullmann JL, et al. Accuracy of computed tomography angiography in the detection of pulmonary embolism in patients with high body weight. *Eur J Intern Med* 2014; **25**: 724–30. doi: <https://doi.org/10.1016/j.ejim.2014.07.003>
40. Megyeri B, Christe A, Schindera ST, Horkay E, Sikula J, Cullmann JL, et al. Diagnostic confidence and image quality of CT pulmonary angiography at 100 kVp in overweight and obese patients. *Clin Radiol* 2015; **70**: 54–61. doi: <https://doi.org/10.1016/j.crad.2014.09.014>
41. Szucs-Farkas Z, Megyeri B, Christe A, Vock P, Heverhagen JT, Schindera ST. Prospective randomised comparison of diagnostic confidence and image quality with normal-dose and low-dose CT pulmonary angiography at various body weights. *Eur Radiol* 2014; **24**: 1868–77. doi: <https://doi.org/10.1007/s00330-014-3208-8>
42. Roggenland D, Peters SA, Lemburg SP, Holland-Letz T, Nicolas V, Heyer CM. CT angiography in suspected pulmonary embolism: impact of patient characteristics and different venous lines on vessel enhancement and image quality. *AJR Am J Roentgenol* 2008; **190**: W351–W359. doi: <https://doi.org/10.2214/AJR.07.3402>
43. Fursevich DM, LiMarzi GM, O'Dell MC, Hernandez MA, Sensakovic WF. Bariatric CT imaging: challenges and solutions. *Radiographics* 2016; **36**: 1076–86. doi: <https://doi.org/10.1148/rg.2016150198>
44. Fujikawa A, Matsuoka S, Kuramochi K, Yoshikawa T, Yagihashi K, Kurihara Y, et al. Vascular enhancement and image quality of CT venography: comparison of standard and low kilovoltage settings. *AJR Am J Roentgenol* 2011; **197**: 838–43. doi: <https://doi.org/10.2214/AJR.10.5424>

45. Kalra MK, Maher MM, Toth TL, Schmidt B, Westerman BL, Morgan HT, et al. Techniques and applications of automatic tube current modulation for CT. *Radiology* 2004; **233**: 649–57. doi: <https://doi.org/10.1148/radiol.2333031150>
46. Bates DD, Tkacz JN, LeBedis CA, Holalkere N. Suboptimal CT pulmonary angiography in the emergency department: a retrospective analysis of outcomes in a large academic medical center. *Emerg Radiol* 2016; **23**: 603–7. doi: <https://doi.org/10.1007/s10140-016-1425-y>
47. Bauer RW, Schell B, Beerers M, Wichmann JL, Bodelle B, Vogl TJ, et al. High-pitch dual-source computed tomography pulmonary angiography in freely breathing patients. *J Thorac Imaging* 2012; **27**: 376–81. doi: <https://doi.org/10.1097/RTI.0b013e318250067e>
48. Langenberger H, Friedrich K, Plank C, Matzek W, Wolf F, Storto ML, et al. MDCT angiography for detection of pulmonary emboli: comparison between equi-iodine doses of iomeprol 400 mgI/mL and iodixanol 320 mgI/mL. *Eur J Radiol* 2009; **70**: 579–88. doi: <https://doi.org/10.1016/j.ejrad.2008.01.058>
49. Nance JW, Henzler T, Meyer M, Apfaltrer P, Braunagel M, Krissak R, et al. Optimization of contrast material delivery for dual-energy computed tomography pulmonary angiography in patients with suspected pulmonary embolism. *Invest Radiol* 2012; **47**: 78–84. doi: <https://doi.org/10.1097/RLI.0b013e31821a2142>
50. Johnson PT, Christensen GM, Fishman EK. IV contrast administration with dual source 128-MDCT: a randomized controlled study comparing 18-gauge nonfenestrated and 20-gauge fenestrated catheters for catheter placement success, infusion rate, image quality, and complications. *AJR Am J Roentgenol* 2014; **202**: 1166–70. doi: <https://doi.org/10.2214/AJR.13.11730>
51. Geyer LL, Schoepf UJ, Meinel FG, Nance JW, Bastarrika G, Leipsic JA, et al. State of the art: Iterative CT reconstruction techniques. *Radiology* 2015; **276**: 339–57. doi: <https://doi.org/10.1148/radiol.2015132766>
52. Kligerman S, Mehta D, Farnadesh M, Jeudy J, Olsen K, White C. Use of a hybrid iterative reconstruction technique to reduce image noise and improve image quality in obese patients undergoing computed tomographic pulmonary angiography. *J Thorac Imaging* 2013; **28**: 49–59. doi: <https://doi.org/10.1097/RTI.0b013e31825412b2>
53. Katz DS, Loud PA, Bruce D, Gittleman AM, Mueller R, Klippenstein DL, et al. Combined CT venography and pulmonary angiography: a comprehensive review. *Radiographics* 2002; **22**(suppl_1): S3–S19. doi: https://doi.org/10.1148/radiographics.22.suppl_1.g02oc17s3
54. Stein PD, Fowler SE, Goodman LR, Gottschalk A, Hales CA, Hull RD, et al. Multidetector computed tomography for acute pulmonary embolism. *N Engl J Med* 2006; **354**: 2317–27. doi: <https://doi.org/10.1056/NEJMoa052367>
55. Lu GM, Zhao Y, Zhang LJ, Schoepf UJ. Dual-energy CT of the lung. *AJR Am J Roentgenol* 2012; **199**(5 Suppl): S40–53. doi: <https://doi.org/10.2214/AJR.12.9112>
56. Zhang LJ, Zhou CS, Schoepf UJ, Sheng HX, Wu SY, Krazinski AW, et al. Dual-energy CT lung ventilation/perfusion imaging for diagnosing pulmonary embolism. *Eur Radiol* 2013; **23**: 2666–75. doi: <https://doi.org/10.1007/s00330-013-2907-x>
57. Thieme SF, Graute V, Nikolaou K, Maxien D, Reiser MF, Hacker M, et al. Dual energy CT lung perfusion imaging-correlation with SPECT/CT. *Eur J Radiol* 2012; **81**: 360–5. doi: <https://doi.org/10.1016/j.ejrad.2010.11.037>
58. Mao X, Wang S, Jiang X, Zhang L, Xu W. Diagnostic value of dual-source computerized tomography combined with perfusion imaging for peripheral pulmonary embolism. *Iran J Radiol* 2016; **13**: e29402. doi: <https://doi.org/10.5812/iranjradiol.29402>
59. Srinivasan S. Dual-energy CT in colorectal cancers: beyond the density measurements. *Diagn Interv Radiol* 2017; **23**: 479–80. doi: <https://doi.org/10.5152/dir.2017.17287>
60. Feuerlein S, Heye TJ, Bashir MR, Boll DT. Iodine quantification using dual-energy multidetector computed tomography imaging: phantom study assessing the impact of iterative reconstruction schemes and patient habitus on accuracy. *Invest Radiol* 2012; **47**: 656–61. doi: <https://doi.org/10.1097/RLI.0b013e31826585bb>
61. Marin D, Pratts-Emanuelli JJ, Mileto A, Husarik DB, Bashir MR, Nelson RC, et al. Interdependencies of acquisition, detection, and reconstruction techniques on the accuracy of iodine quantification in varying patient sizes employing dual-energy CT. *Eur Radiol* 2015; **25**: 679–86. doi: <https://doi.org/10.1007/s00330-014-3447-8>
62. Albrecht MH, Scholtz JE, Hüters K, Beerers M, Bucher AM, Kaup M, et al. Advanced image-based virtual monoenergetic dual-energy CT angiography of the abdomen: optimization of kiloelectron volt settings to improve image contrast. *Eur Radiol* 2016; **26**: 1863–70. doi: <https://doi.org/10.1007/s00330-015-3970-2>
63. Weiss J, Notohamiprodjo M, Bongers M, Schabel C, Mangold S, Nikolaou K, et al. Effect of noise-optimized monoenergetic postprocessing on diagnostic accuracy for detecting incidental pulmonary embolism in portal-venous phase dual-energy computed tomography. *Invest Radiol* 2017; **52**: 142–7. doi: <https://doi.org/10.1097/RLI.0000000000000319>
64. Fraser JD, Anderson DR. Deep venous thrombosis: recent advances and optimal investigation with US. *Radiology* 1999; **211**: 9–24. doi: <https://doi.org/10.1148/radiology.211.1.r99ap459>
65. Anvari A, Forsberg F, Samir AE. A primer on the physical principles of tissue harmonic imaging. *Radiographics* 2015; **35**: 1955–64. doi: <https://doi.org/10.1148/rg.2015140338>
66. Rosenthal SJ, Jones PH, Wetzel LH. Phase inversion tissue harmonic sonographic imaging: a clinical utility study. *AJR Am J Roentgenol* 2001; **176**: 1393–8. doi: <https://doi.org/10.2214/ajr.176.6.1761393>
67. Stein EG, Haramati LB, Chamarthy M, Sprayregen S, Davitt MM, Freeman LM. Success of a safe and simple algorithm to reduce use of CT pulmonary angiography in the emergency department. *AJR Am J Roentgenol* 2010; **194**: 392–7. doi: <https://doi.org/10.2214/AJR.09.2499>
68. Glaser JE, Chamarthy M, Haramati LB, Esses D, Freeman LM. Successful and safe implementation of a trinary interpretation and reporting strategy for V/Q lung scintigraphy. *J Nucl Med* 2011; **52**: 1508–12. doi: <https://doi.org/10.2967/jnumed.111.090753>
69. Waxman AD, Bajc M, Brown M, Fahey FH, Freeman LM, Haramati LB, et al. Appropriate use criteria for ventilation-perfusion imaging in pulmonary embolism: summary and excerpts. *J Nucl Med* 2017; **58**: 13n–15.
70. Freeman LM, Stein EG, Sprayregen S, Chamarthy M, Haramati LB. The current and continuing important role of ventilation-perfusion scintigraphy in evaluating patients with suspected pulmonary embolism. *Semin Nucl Med* 2008; **38**: 432–40. doi: <https://doi.org/10.1053/j.semnucmed.2008.07.001>
71. 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; **298**: 2743–53. doi: <https://doi.org/10.1001/jama.298.23.2743>
72. ACR appropriateness criteria® suspected pulmonary embolism [Internet]. *J Am Coll Radiol* 2016; **14**: S350–S361.
73. Onyedika C, Glaser JE, Freeman LM. Pulmonary embolism: role of ventilation-perfusion scintigraphy. *Semin Nucl Med*

- 2013; **43**: 82–7. doi: <https://doi.org/10.1053/j.semnuclmed.2012.11.002>
74. Bhatia KD, Ambati C, Dhaliwal R, Paschkewitz R, Hsu E, Ho B, et al. SPECT-CT/VQ versus CTPA for diagnosing pulmonary embolus and other lung pathology: pre-existing lung disease should not be a contraindication. *J Med Imaging Radiat Oncol* 2016; **60**: 492–7. doi: <https://doi.org/10.1111/1754-9485.12471>
 75. Roach PJ, Schembri GP, Bailey DL. V/Q scanning using SPECT and SPECT/CT. *J Nucl Med* 2013; **54**: 1588–96. doi: <https://doi.org/10.2967/jnumed.113.124602>
 76. Bajc M, Olsson CG, Olsson B, Palmer J, Jonson B. Diagnostic evaluation of planar and tomographic ventilation/perfusion lung images in patients with suspected pulmonary emboli. *Clin Physiol Funct Imaging* 2004; **24**: 249–56. doi: <https://doi.org/10.1111/j.1475-097X.2004.00546.x>
 77. Vanhecke TE, Berman AD, McCullough PA. Body weight limitations of United States cardiac catheterization laboratories including restricted access for the morbidly obese. *Am J Cardiol* 2008; **102**: 285–6. doi: <https://doi.org/10.1016/j.amjcard.2008.03.050>
 78. Hibbert B, Simard T, Wilson KR, Hawken S, Wells GA, Ramirez FD, et al. Transradial versus transfemoral artery approach for coronary angiography and percutaneous coronary intervention in the extremely obese. *JACC Cardiovasc Interv* 2012; **5**: 819–26. doi: <https://doi.org/10.1016/j.jcin.2012.04.009>
 79. De Gregorio MA, Guirola JA, Lahuerta C, Serrano C, Figueredo AL, Kuo WT. Interventional radiology treatment for pulmonary embolism. *World J Radiol* 2017; **9**: 295–303. doi: <https://doi.org/10.4329/wjr.v9.i7.295>
 80. Mostafa A, Briasoulis A, Telila T, Belgrave K, Grines C. Treatment of massive or submassive acute pulmonary embolism with catheter-directed thrombolysis. *Am J Cardiol* 2016; **117**: 1014–20. doi: <https://doi.org/10.1016/j.amjcard.2015.12.041>
 81. Kuo WT, Banerjee A, Kim PS, DeMarco FJ, Levy JR, Facchini FR, et al. Pulmonary embolism response to fragmentation, embolectomy, and catheter thrombolysis (PERFECT): Initial results from a prospective multicenter registry. *Chest* 2015; **148**: 667–73. doi: <https://doi.org/10.1378/chest.15-0119>
 82. Aberle D, Charles H, Hodak S, O'Neill D, Oklu R, Deipolyi AR. Optimizing care for the obese patient in interventional radiology. *Diagn Interv Radiol* 2017; **23**: 156–62. doi: <https://doi.org/10.5152/dir.2016.16230>
 83. Mokdad AH, Ford ES, Bowman BA, Dietz WH, Vinicor F, Bales VS, et al. Prevalence of obesity, diabetes, and obesity-related health risk factors, 2001. *JAMA* 2003; **289**: 76–9. doi: <https://doi.org/10.1001/jama.289.1.76>
 84. Kurukulasuriya LR, Stas S, Lastra G, Manrique C, Sowers JR. Hypertension in obesity. *Med Clin North Am* 2011; **95**: 903–17. doi: <https://doi.org/10.1016/j.mcna.2011.06.004>
 85. Chatterjee S, Chakraborty A, Weinberg I, Kadakia M, Wilensky RL, Sardar P, et al. Thrombolysis for pulmonary embolism and risk of all-cause mortality, major bleeding, and intracranial hemorrhage: a meta-analysis. *JAMA* 2014; **311**: 2414–21. doi: <https://doi.org/10.1001/jama.2014.5990>