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Multislice CT imaging of pulmonary embolism

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Abstract In recent years CT has been established as the method of choice for the diagnosis of central pulmonary embolism (PE) to the level of the segmental arteries. The key advantage of CT over competing modalities is the reliable detection of relevant alternative or additional disease causing the patient's symptoms. Although the clinical relevance of isolated peripheral emboli remains unclear, the alleged poor sensitivity of CT for the detection of such small clots has to date prevented the acceptance of CT as the gold standard for diagnosing PE. With the advent of multislice CT we can now cover the entire chest of a patient with 1-mm slices within one breath-hold. In comparison with thicker sections, the detection rate of subsegmental emboli can be significantly increased with 1-mm slices. In addition, the interobserver correlation which can be achieved with 1-mm sections by far exceeds the reproducibility of competing modalities. Meanwhile use of multislice CT for a combined diagnosis of PE and deep venous thrombosis with the same modality appears to be clinically accepted. In the vast majority of patients who receive a combined thoracic and venous multislice CT examination the scan either confirms the suspected diagnosis or reveals relevant alternative or additional disease. The therapeutic regimen is usually chosen based on the functional effect of embolic vascular occlusion. With the advent of fast CT scanning techniques, also functional parameters of lung perfusion can be non-invasively assessed by CT imaging. These advantages let multislice CT appear as an attractive modality for a non-invasive, fast, accurate, and comprehensive diagnosis of PE, its causes, effects, and differential diagnoses.

Keywords Pulmonary embolism · Lung · Lung perfusion · Pulmonary hypertension · Multislice CT · Multisection CT · Multidetector row CT

Introduction

Recent years have seen an increasing importance of CT in the diagnosis of pulmonary embolism (PE), mainly brought about by the advent of fast CT image acquisition techniques [1, 2, 3, 4]. Competing imaging modalities are on the decline: nuclear scanning, once the first line of defense in the diagnostic algorithm of PE, is withdrawing to diagnostic niches due to limited availability [5], poor inter-observer correlation [6], and notorious lack of specificity [7]. Pulmonary angiography, the one-time gold standard for the diagnosis of PE, is becoming increasingly tarnished [8, 9]. Magnetic resonance imaging may be a promising tool for the diagnosis of PE [10, 11] in the future but to date has not found widespread use in emergency medicine due mainly to its long examination times and difficulties in patient monitoring. In contrast, CT has become established as a

widely available [5], safe, cost-effective [12], and accurate modality for the quick and comprehensive [13] diagnosis of the pulmonary circulation and the deep venous system [14]. The evident advantages of CT for the diagnosis of PE have become further enhanced by the introduction of multislice CT technology [14, 15, 16, 17]. It is now feasible to acquire a 1-mm scan of the entire thorax within one breath-hold. Perceived limitations of CT for the depiction of peripheral emboli are thus overcome. Herein we discuss the clinical impact of multislice CT on the diagnostic algorithm of suspected PE.

Diagnosis of pulmonary embolism with CT: general considerations

The most important advantage of CT over competing imaging modalities is that the mediastinal and parenchymal structures can be evaluated [4]. This allows directly visualizing the embolus and the distension of the right cardiac cavities which is a measure of the right heart load of the patient [18]. Moreover, it has been shown that up to two-thirds of patients with initially suspected PE receive other diagnoses [19]. With CT potentially life-threatening alternative causes of the clinical signs and symptoms in a patient with chest pain and a normal radiograph, such as aortic dissection, can be reliably identified [20]. In addition, it seems to be largely unknown that CT also appears to be the diagnostic modality of choice in pregnant patients with suspected PE. Even with high-dose scanner settings, the average fetal radiation dose with CT is significantly less than nuclear perfusion lung scanning so that CT for suspected PE may be acceptable in pregnancy [21].

Despite these eminent advantages, a case has frequently been made against CT imaging of PE, based on its alleged lack of accuracy for peripheral emboli. The significance of such small emboli in the periphery of the lung is uncertain and is discussed later. Computed tomography meanwhile has demonstrated its high accuracy for the detection of PE down to the segmental arterial level [22]. Its ability to detect subsegmental emboli rivals that of invasive pulmonary arteriography: In recent analyses the inter-observer agreement for detection of subsegmental emboli with pulmonary angiography ranged between 45 and 66 % [8, 9]. With CT similar accuracy for the detection of subsegmental emboli could be achieved back in 1995 with a first-generation spiral scanner without subsecond image acquisition capability [22]; thus, there is no clinical advantage of subjecting a patient to invasive pulmonary angiography for mere diagnostic purposes, a procedure which carries a small but definite risk [23]. Also, missing small peripheral emboli with either CT or nuclear scanning does not seem to seriously affect patient outcome. The frequency of clinical diagnoses of PE after a negative CT scan is low (1 %), and lower than that after a negative or low-probability V-Q scan (3 %) [24]; thus, even single-slice spiral CT is a reliable imaging tool for excluding clinically relevant PE so that anticoagulation can be safely withheld when the CT scan is normal [24].

Computed tomography is little observer-dependent [25] and clearly outperforms scintigraphy in terms of inter-observer correlation. In a recent study inter-observer agreement for the diagnosis of PE was excellent for spiral-CT angiography (= 0.72) and only moderate for ventilation–perfusion radionuclide lung scanning (= 0.22) [6]. In addition, CT proved to be the most cost-effective modality in the diagnostic algorithm of PE [12], which is becoming of increasing importance in the present socio-economic environments.

Diagnosis of PE with multislice CT

Multislice CT for imaging acute PE

The introduction of multislice technology is the single most important development in the field of CT imaging after the advent of spiral CT [26]. In the current scanner generation the single detector bank of conventional spiral scanners has been replaced by multiple detector banks, which can be combined during readout to acquire four slices simultaneously. The most prominent feature of this technology is increased speed. Compared with conventional 1-s rotation single-slice CT, the same volume can be covered up to eight times faster with identical section thickness [14]. Another option is to use narrower collimation in order to increase spatial resolution and reduce partial-volume averaging. The gain in image acquisition speed will further increase in the near future with the introduction of more advanced generations of multislice CT scanners with added detector rows and new concepts of image acquisition and data transport.

For imaging of suspected PE where both speed and attention to detail are of crucial importance, we make use of this increased image acquisition speed in a variety of ways. In the emergency situation, in dyspneic or uncooperative patients the presence of central emboli (i.e., including segmental pulmonary arteries) must be verified or ruled out within a few seconds. To this end, we use a multislice CT (Somatom VolumeZoom, Siemens, Forchheim, Germany) protocol that comprises 500-ms rotation, pitch of 6, and 4×2.5-mm collimation. With this protocol the entire thorax (25 cm) can be covered within 8 s. This unprecedented speed results in optimal image quality even in the most dyspneic or uncooperative individuals and represents an invaluable gain in our ability to care for critically ill patients (Fig. 1). If only the pulmonary vessels are to be evaluated, the amount

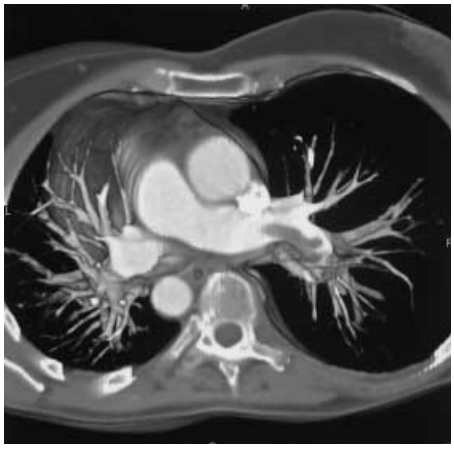

Fig. 1 Acute pulmonary embolism (PE). A central embolus extends into the right main pulmonary artery. Multislice CT scan protocol: 2.5-mm collimation; pitch 6; total scan time 8 s. (Siemens, Forchheim, Germany) volume rendering seen from above

of contrast material can be substantially reduced; the latter is an important advantage in the elderly population with impaired cardiac and renal function in whom excessive volume load caused by large quantities of hyperosmolar contrast media must be avoided.

Multislice CT for imaging peripheral pulmonary arteries

The clinical significance of small peripheral emboli in segmental and subsegmental pulmonary arteries in the absence of central emboli is uncertain. It has been shown that 6% [7] to 30% [27] of patients with documented PE present with clots only in subsegmental and smaller arteries. It is assumed that one important function of the lung is to prevent small emboli from entering the arterial circulation [28]. Such emboli are thought to form even in healthy individuals, although this notion has never been substantiated [29]. Controversy also exists as to whether the treatment of small emboli, once detected, may result in a better clinical outcome for patients [24, 27, 28, 30, 31]. In the overwhelming majority of cases missing small peripheral emboli does not seem to adversely affect patient outcome [24]. There seems to be agreement, however, that the presence of peripheral emboli may be an indicator for current deep vein thrombosis thus potentially heralding more severe embolic events [19, 27, 32]. A burden of small peripheral emboli may also have prognostic relevance in individuals with cardio-pulmonary restrictions [24, 27, 28] and for the development of chronic pulmonary hypertension in patients with thromboembolic disease [27]. Before the argument over the clinical significance of small clots is finally settled and as long as the accuracy of CT for detecting peripheral emboli is being questioned, the quest to improve the diagnostic quality of CT pulmonary angiography appears to be justified.

It could be shown that superior visualization of segmental and subsegmental pulmonary arteries can be achieved with 2- vs 3-mm collimation [33, 34], probably due to reduced volume averaging and improved analysis of small-sized vessels with progressively thinner slices. However, using conventional single-slice CT the range, which can be covered with thin collimation within one breath-hold, is limited even if high pitch factors are used [3, 33]. Use of 2-mm collimation single-slice CT with a pitch of 2 (5.3-mm table feed/s) which was proposed as the optimized acquisition protocol [33] covers a volume from the aortic arch to the base of the heart (10–12 cm) within 19 to 23 s.

In addition, in many instances the 0.75-s slice acquisition time of conventional single-slice CT is still too long to effectively reduce cardiac pulsation artifacts in the vicinity of the heart [35]. Segmental and subsegmental arteries in paracardiac lung segments thus tend to be blurred, so that definitive exclusion of isolated emboli in these vessels is not always feasible [3].

The advent of multislice CT allows covering extensive volumes with thin collimation within a single breath-hold. A 1-mm collimation multislice CT acquisition with 500-ms gantry rotation time and a pitch of 6 (12-mm table feed/s) covers a range from the aortic arch to the base of the heart in 8–10 s. Inclusion of the entire chest in the multislice CT examination enhances the diagnostic value of the study, since alternative disease in the periphery of the lung can also be detected; therefore, if a meticulous analysis of peripheral pulmonary arteries for the exclusion of small clots is required, e.g., in patients with poor cardio-respiratory reserve, we cover the entire chest (25 cm) with 1-mm collimation and pitch of 6 within 20 s. Thus, despite of the use of thinner, 1-mm collimation, the acquisition speed can be significantly increased with multislice CT. At the same time, the high spatial resolution of 1-mm sections, if read from a monitor, significantly increases the detection rate of segmental and subsegmental pulmonary emboli compared with thicker sections [36]. This increase in the rate of detection likely is directly related to the accurate depiction, without volume averaging, of progressively thinner vessels by use of thinner sections. The improved visualization with 1-mm multislice CT is most striking in peripheral arteries with an anatomic course parallel to the scan plane. Such vessels tend to be most affected by volume averaging if thicker slices are used. The high spatial resolution along the scan axis of a 1-mm multislice CT data set, however, allows an accurate evaluation of the full course of such vessels (Fig. 2). The interobserver correlation for confident detection of subsegmental emboli with 1-mm multislice CT by far exceeds the reproducibility of competing modalities, i.e., invasive pulmonary angiography [36]. Thus, tradi-

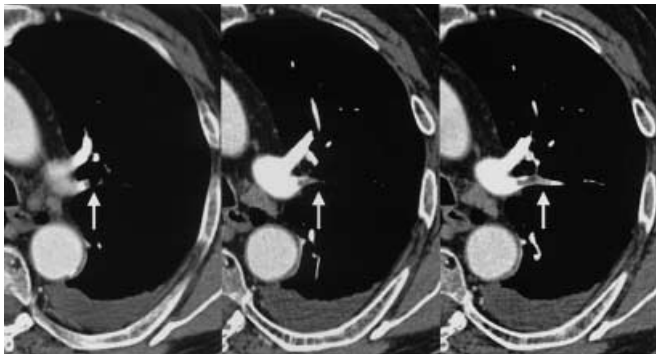

Fig. 2 A 70-year-old man. Three-millimeter (**left**) and 2-mm (**middle**) axial reconstructions of a contrast-enhanced multislice CT data set suggest the presence of thrombus in a segmental artery supplying the posterior segment of the left upper lobe of the lung *(arrows)*. Only 1-mm reconstruction (**right**) of the data set allows following the entire course of the segmental artery and unanimous visualization of the filling defect within the posterior subsegmental branch

tional limitations of CT for the diagnosis of small peripheral emboli appear to be overcome with the advent of multislice CT.

While multislice CT increases our diagnostic capabilities, the massive amount of data which is generated by this technique puts significant strain on any image analysis and archiving system. A 1-mm multislice CT study in a patient with suspected pulmonary embolism routinely results in 200–300 individual axial images. Reading of such a study is only feasible by use of digital workstations that allow viewing in "scroll-through" or "cine" mode. Also, extensive PACS storage capacities are an essential need for successful routine performance of multislice CT in a busy clinical environment. Adapting this environment to the new demands which are generated by the introduction of ever-faster scanning techniques is not a trivial task. New modalities for data transfer, data archiving, and image interpretation will have to be devised in order to make full use of the vast potential of MSCT imaging.

Multislice CT for evaluating pulmonary hypertension

Pulmonary hypertension (PH) of the precapillary pulmonary circulation is a diagnostic challenge. The host of potential underlying disorders includes idiopathic disease, recurrent embolism, and structural lung changes among other more readily identifiable causes [37]. Computed tomography has traditionally been an important tool in the diagnostic algorithm of PH allowing for an accurate assessment of both, pathogenesis and extent of the disease. High-resolution CT (HRCT) is the gold standard to evaluate a patient with suspected PH for structural lung changes that may cause increased pre- or postcapillary pressure within the lung vessels. Mosaic attenuation on HRCT (Fig. 3), combined with distal pruning of pulmonary arteries, is a tell-tale sign of impaired pulmonary perfusion due to recurrent peripheral embolism as the underlying cause. Contrast-enhanced spiral CT allows for direct visualization of more centrally located chronic thromboemboli and helps to determine if the disease is amenable to surgical thrombendarterectomy (Fig. 3). If neither structural lung changes nor signs of thromboembolism are found in the absence of other identifiable etiologies for PH, such as congenital heart disease or tumor embolism, a diagnosis of primary pulmonary hypertension (PPH) is usually considered. Since the differential diagnosis of PH includes diseases with both focal and diffuse character, the entire pathology frequently cannot be appreciated with a single CT technique. Conventional thick-collimation spiral CT may not suffice to assess interstitial changes. If only HRCT is performed, focal pathology, such as thromboembolism, is easily missed due to the high-frequency reconstruction algorithms and because scans are acquired at only every 10–20 mm. In patients with suspected PH it is therefore often necessary to perform both spiral CT and HRCT for a comprehensive assessment of the underlying pathology. Now a single, breath-held, 1-mm collimation multislice CT acquisition generates a set of raw data that provides all options for image reconstruction, allowing addressing multiple diagnostic problems by performing a single contrast-enhanced scan (Fig. 3). In patients with suspected PH we routinely perform a 1-mm reconstruction of the entire chest which, if read from a monitor, allows a highly sensitive detection of small peripheral thrombotic changes. In addition, from the same set of raw data 5-mm contiguous lung sections and 1-mm HRCT sections at every 1 cm are routinely performed (Fig. 3b); thus, from a single set of raw data a comprehensive analysis of gross and diffuse lung changes and of thromboembolic disease becomes feasible.

Functional multislice CT imaging of lung perfusion

To date, CT has not permitted the functional evaluation of pulmonary microcirculation during pulmonary embolism. The choice of the adequate therapeutic regimen, however, critically hinges on an accurate evaluation of the functional effect of thromboemboli on lung perfusion. If large percentages of the lung parenchyma are affected by embolic occlusion, imminent right heart failure warrants a more aggressive regimen, such as thrombolysis, which carries a small but definite risk [38, 39]; thus, the quantitative assessment of the effect of PE on tissue perfusion may bear more important information for patient management than the direct visualization of emboli by CT angiography alone. It has been

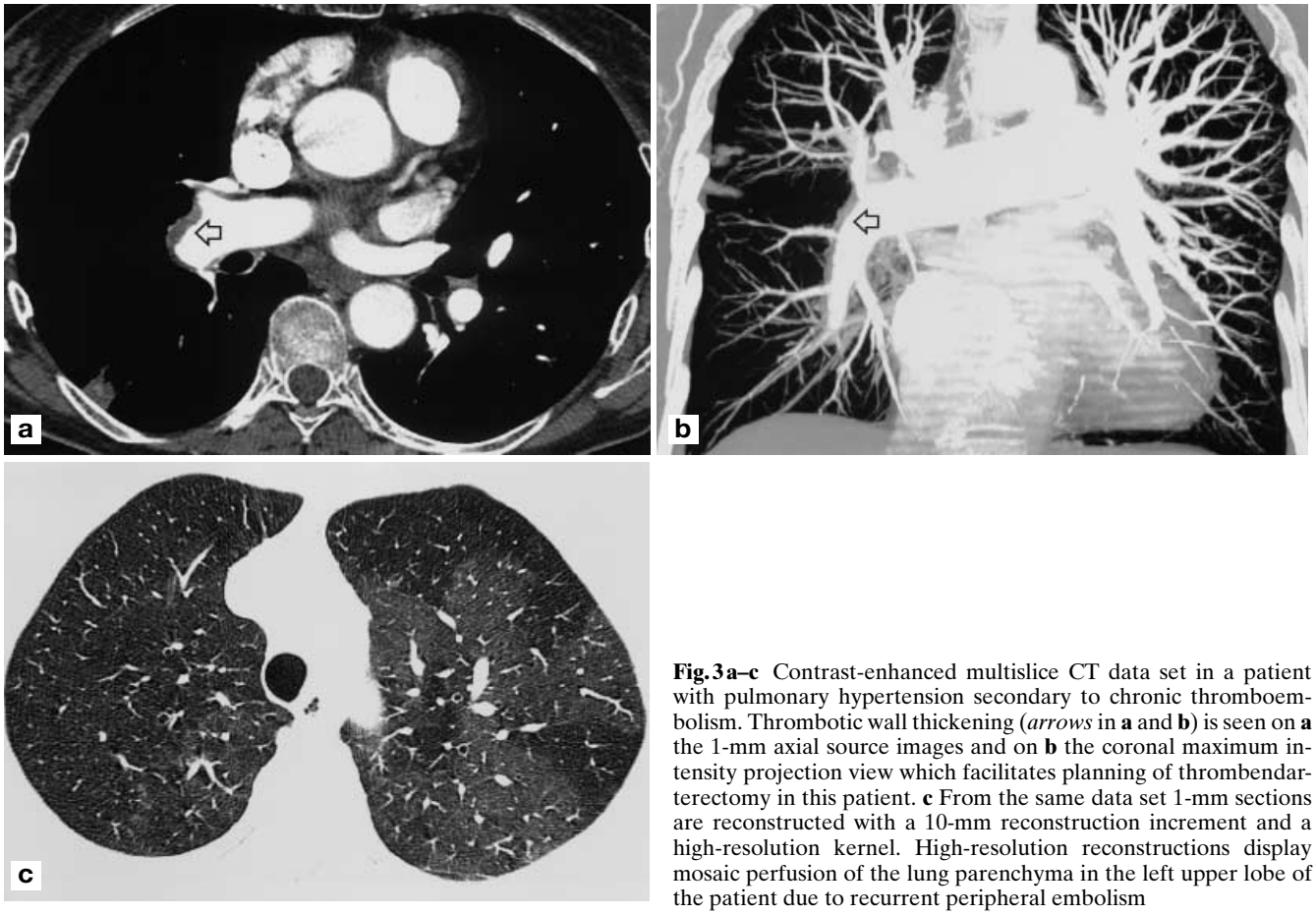

Fig. 3 a–c Contrast-enhanced multislice CT data set in a patient with pulmonary hypertension secondary to chronic thromboembolism. Thrombotic wall thickening (*arrows* in **a** and **b**) is seen on **a** the 1-mm axial source images and on **b** the coronal maximum intensity projection view which facilitates planning of thrombendarterectomy in this patient. **c** From the same data set 1-mm sections are reconstructed with a 10-mm reconstruction increment and a high-resolution kernel. High-resolution reconstructions display mosaic perfusion of the lung parenchyma in the left upper lobe of the patient due to recurrent peripheral embolism

shown that with the advent of fast CT scanning techniques functional parameters of lung perfusion can be non-invasively assessed by means of CT imaging (Table 1) [4, 40, 41, 42]. Based on these experiences dedicated image-processing tools are being developed for use with high-resolution multislice CT. We pursue different approaches for visualization of lung perfusion on a prototype of a specially designed software platform (LungCare, Siemens). "Perfusion-weighted display" (Fig. 4), for instance, allows color-encoded display of lung parenchyma enhancement based on routine high-resolution multislice CT data which is contrast en-

Table 1 Multislice CT imaging parameters. *DVT* deep venous thrombosis

	Collimation (mm)	Table feed (mm/s)	Gantry rotation (s)	Pitch	kV	mAs	Contrast volume (ml)	Flow (ml/s)	Delay (s)	Reconstruction/increment (mm)
Pulmonary arteries high speed	4 × 2.5	30	0.5	6	120	120	80	4	18	2.5/2 5/5 (lung)
Pulmonary arteries high resolution	4 × 1	12	0.5	6	120	120	120	4	18	1.25/1 5/5 (lung)
Pulmonary hypertension	4 × 1	8	0.75	6	120	120	120	4	20	1.25/1 5/5 (lung); 1.25/10 (high resolution)
Veins in suspected PE and DVT	4 × 5 mm	70	0.5	7	120	120	No additional contrast	–	150 s total delay	5/5

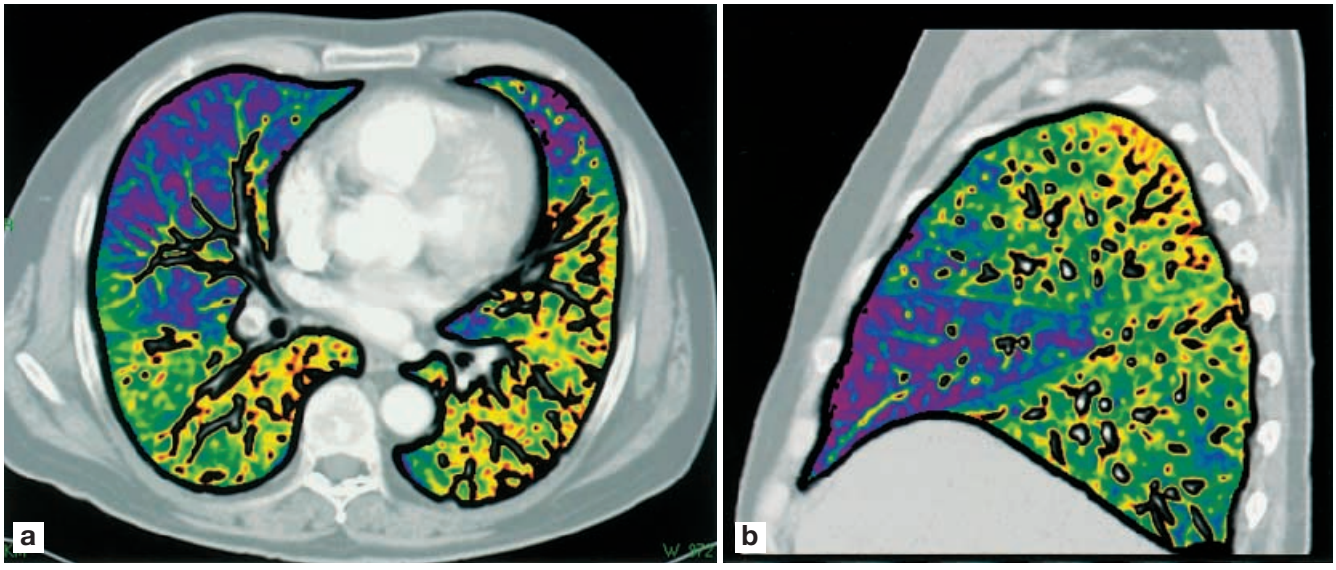

Fig. 4a, b A 58-year-old man with PE in the right middle lobe. **a** Perfusion-weighted color-coded display of a transaxial, contrast-enhanced multislice CT data set enables delineation of the resulting perfusion defect in the dependent parenchyma. Perfusion-weighted display allows estimating the percentage of lung parenchyma that is functionally affected by thromboembolism. Superimposing functional data on the morphological scan aids spatial orientation. **b** Reconstruction of functional image data in the sagittal imaging plane is made feasible by the isotropic nature of a high-resolution multislice CT data set and further aids localization and visualization of perfusion defects. In addition, on reformats in arbitrary image orientations gravity-dependent distribution of lung perfusion can be more accurately assessed and better differentiated from embolic perfusion deficits compared with transaxial scans alone

hanced with a sharp bolus of low-viscosity contrast material (Accupaque 300, Nycomed-Amersham, Oslo, Norway). In a first step, the individual axial slices of such a multislice CT study provide the usual structural information with direct visualization of emboli. For functional information the lung parenchyma is then extracted from the individual axial images using threshold-based contour-finding algorithms. Dedicated filters are applied to the resulting images in order to optimally display differences in enhancement on spectral color-coded maps. Additional overlay of the parenchymal color map onto the original CT image is used to enhance visualization of spatial relationships (Fig. 4a). Due to the isotropic nature of a 1-mm multislice CT data set, color-coded images can be viewed in arbitrary imaging planes (Fig. 4b). In each case the findings of functional multislice CT imaging must also be correlated to the structural information provided by the individual axial slices on which the functional study is based. This way, since input from both structural and functional scanning is used for a comprehensive diagnosis, altered perfusion parameters based on structural lung changes can be recognized as such and therefore should not impair the utility of functional multislice CT. We anticipate this method to evolve into a valuable adjunct to CT pulmonary angiography by providing both structural and functional information using the same modality. The well-established accuracy of CT for the depiction of emboli and thoracic anatomy is thus supplemented by an effective means to quantitatively assess the functional effect of thromboemboli on lung perfusion. This way, a comprehensive diagnosis is feasible within a few minutes, without having to subject a patient to multiple expensive and time-consuming tests requiring transportation and advanced logistics.

Multislice CT for imaging deep venous thrombosis

Combined multislice CT venography and pulmonary angiography is a diagnostic test that screens for pulmonary embolism and deep venous thrombosis (DVT) using a single contrast medium infusion. This technique has been proposed as a cost-effective means for excluding lower-extremity venous thrombosis in patients undergoing CT pulmonary angiography [43]. Key advantages allow that no additional contrast media needs to be injected to evaluate both the pulmonary vessels and the deep venous system. Meanwhile, use of CT for this purpose seems to be clinically established [44, 45, 46, 48]. We use the volume covering capabilities, which have become available with multislice CT for a comprehensive diagnosis of PE and DVT in patients without known source of emboli. In this setting, we administer a full dose of 120 cc of contrast material while scanning the pulmonary arteries and then cover the entire subphrenic venous system during venous enhancement

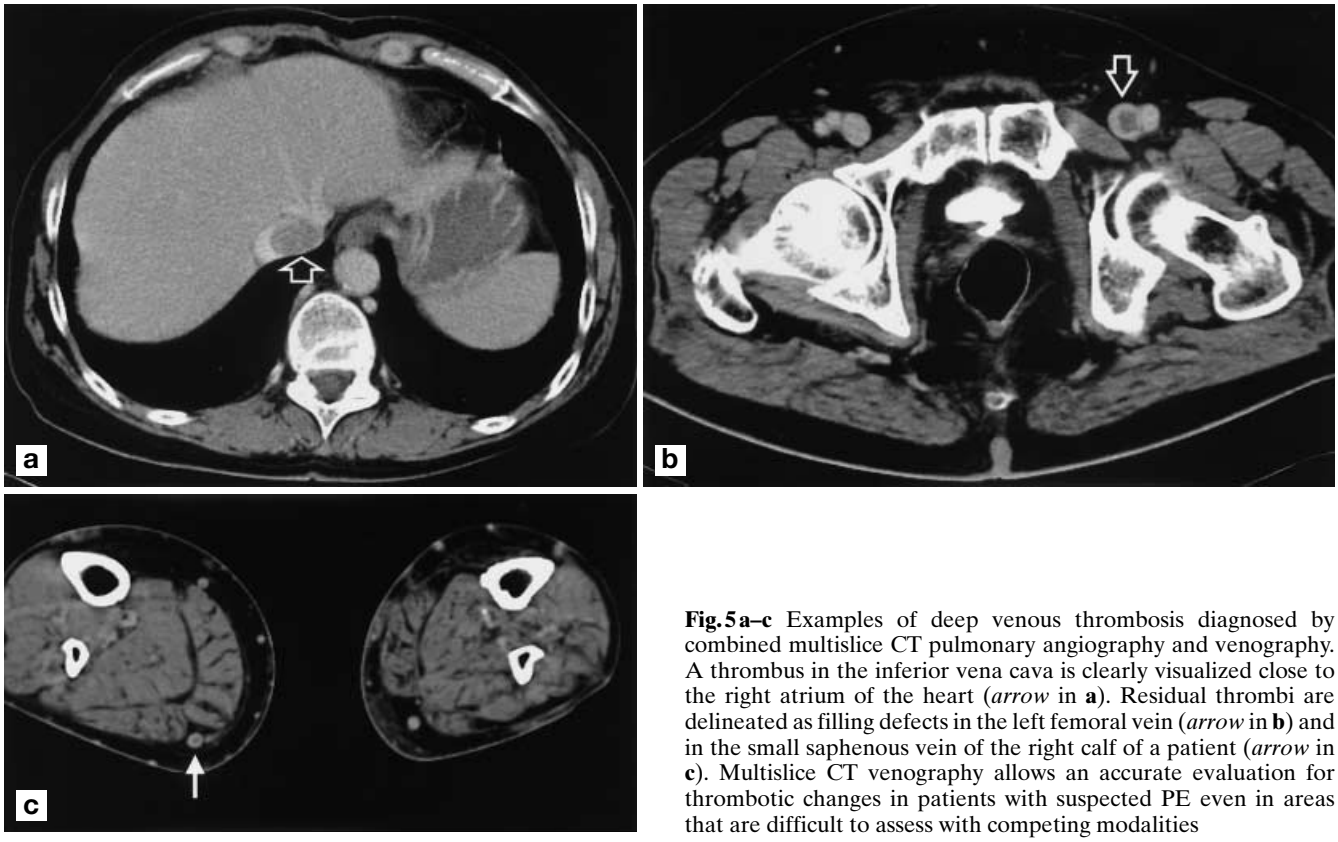

Fig. 5 a–c Examples of deep venous thrombosis diagnosed by combined multislice CT pulmonary angiography and venography. A thrombus in the inferior vena cava is clearly visualized close to the right atrium of the heart (*arrow* in **a**). Residual thrombi are delineated as filling defects in the left femoral vein (*arrow* in **b**) and in the small saphenous vein of the right calf of a patient (*arrow* in **c**). Multislice CT venography allows an accurate evaluation for thrombotic changes in patients with suspected PE even in areas that are difficult to assess with competing modalities

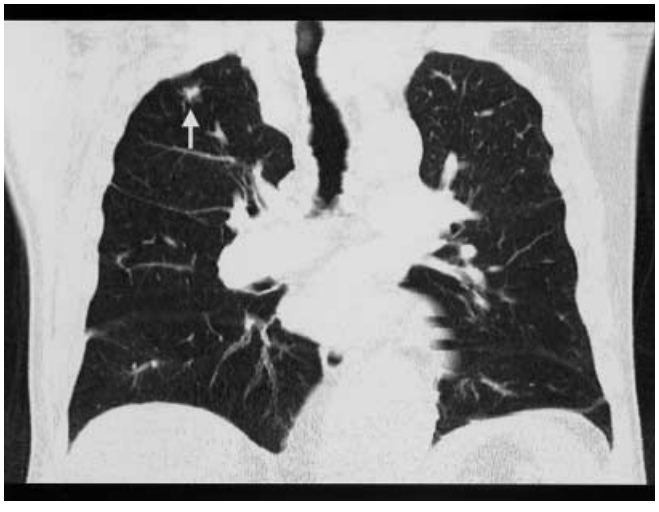

Fig. 6 Incidentally found T1 peripheral adenocarcinoma *(arrow)* in the right upper lobe of a patient with central PE. Volume-rendered display of a contrast-enhanced high-resolution multislice CT pulmonary angiogram. Direct visualization of emboli and of relevant alternative or additional disease is the key advantage of CT over competing modalities for the diagnosis of PE

without any additional contrast material. Using 500-ms rotation, 4 × 5-mm collimation and pitch 7, a 100-cm volume can be covered in approximately 20 s. Scanning for deep venous thrombosis in patients with suspected pulmonary embolism is the only vascular indication where a collimation of 4 × 5 mm is used at our institute in order to achieve a maximum of volume coverage with a minimum of radiation exposure. In a patient with acute PE who is bound for the intensive care unit, a comprehensive diagnosis of the extent of thromboembolic disease, the source of emboli, and potential residual thrombosis can be diagnosed in a single session by using this approach. Computed tomography may even be advantageous over Doppler sonography and conventional venography since extensive residual thrombosis in the abdominal and pelvic venous system may be better visualized by use of CT (Fig. 5a). Thrombosis in calf veins may be less accurately depicted with CT (Fig. 5c) but usually does not represent a life-threatening condition. In the vast majority of patients who receive a combined thoracic and venous multislice CT examination, the scan either confirms the suspected diagnosis or reveals relevant alternative or additional disease (Fig. 6). Experience has also taught us that repeated referrals for suspected malignancy as the underlying cause for PE are markedly reduced by performing

combined pulmonary multislice CT angiography and venography as an initial examination for suspected acute PE; thus, using this approach time-consuming and expensive additional examinations in critically ill patients can be avoided.

In conclusion, multislice CT in our experience represents an attractive means for a safe, cost-effective, highly accurate, and comprehensive diagnosis of PE, its extent, causes, differential diagnoses, and functional effects. With the advent of this technology perceived limitations of CT for the diagnosis of PE should be overcome. The gain in image acquisition speed will further increase in the near future with the introduction of more advanced generations of multislice CT scanners with added detector rows and new concepts of image acquisition and data transport. The advantages of this modality that became evident with the current generation of multislice CT scanners will thus be further enhanced to the benefit of our patients.

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