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Enhancing Lung Scintigraphy With Single-Photon Emission Computed Tomography

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Although widely used for many years in the assessment of pulmonary embolism, planar ventilation-perfusion (V/Q) scintigraphy has well-recognized limitations. Single-photon emission computed tomography (SPECT) imaging, which can be readily performed in most modern nuclear medicine centers equipped with multihead gamma cameras, overcomes many of these limitations through its ability to generate 3-dimensional imaging data. V/Q SPECT has been shown to have a greater sensitivity and specificity than planar imaging and has a lower nondiagnostic rate. For reporting clinicians who may be reluctant to abandon conventional planar V/Q images, planar-like images can also be readily obtained from V/Q SPECT with the use of postacquisition techniques. The use of SPECT can also facilitate advances in V/Q imaging, including the generation of parametric V:Q ratio images, coregistration with computed tomography, respiratory gating, and more accurate quantification of regional lung function. Although direct comparisons in the literature are limited in number, V/Q SPECT appears to have comparable, or greater, sensitivity than multidetector computed tomography pulmonary angiography and is not associated with contrast-related complications such as allergy and nephropathy. It also involves significantly less radiation dose to breast tissue, an important consideration, particularly in young women. For the V/Q scan to remain relevant in the evaluation of patients with suspected pulmonary embolism, it is essential that image data are obtained so as to maximize their accuracy and diagnostic usefulness. V/Q SPECT can achieve this and, furthermore, may have a role in conditions other than pulmonary embolism, including both clinical and research fields.
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The accurate diagnosis of pulmonary embolism (PE) continues to be a challenge for both clinicians and imaging specialists. Misdiagnosis is problematic because untreated PE is reported to have a mortality rate of up to 30%, and unnecessary treatment with anticoagulation places the patient at risk of bleeding.[1-3] Historically, ventilation-perfusion (V/Q) lung scan and digital subtraction pulmonary angiography have been used as imaging investigations in the diagnosis of potential PE.[4] More recently, radiographic computed tomography pulmonary angiography (CTPA) has been increasingly used.[4] Although pulmonary angiography has previously been considered the gold standard investigation for PE, it is performed less frequently today because of its limited availability, requirement for operator expertise, and invasive nature.[4] To add to this, pulmonary angiography has recently been demonstrated to have less-than-optimal diagnostic accuracy.[5] Consequently, the V/Q scan and CTPA are the 2 most widely available and used investigations to image patients with suspected PE today.

Although V/Q scintigraphy has been used for more than 30 years in the assessment of patients with suspected PE, this technique is widely recognized as having limitations.[6-10] When the lungs are imaged in only two dimensions (2D), as occurs with planar imaging, there is significant overlap of anatomical segments, hence accurate assignment of defects to specific lung segments is difficult. Embolic defects may not be detected if there is "shine-through" occurring from underlying lung segments with normal perfusion.[9] The size and shape of each lung segment varies and accurately determining the extent of embolic involvement in each individual segment can be problematic.[9,11,12] In addition to these inherent technical limitations of planar lung scintigraphy, there

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are the problems posed by the widely used probabilistic PIOPED reporting schema.[13-17] PE is not a condition in which clinicians welcome "indeterminate" results and it is desirable to reduce such reports as much as possible.

SPECT is widely used in many areas of radionuclide imaging today because of its ability to image in three dimensions (3D). It has been shown to be superior to planar imaging in the evaluation of many conditions, such as assessing myocardial perfusion and brain and liver imaging.[18] In contrast to planar imaging, SPECT avoids the problems introduced by segmental overlap and "shine-through" of adjacent lung, making it better able to image all segments of the lungs and more accurately define the size and location of perfusion defects.[9] For these reasons, it would be expected that SPECT V/Q scintigraphy should be superior to planar imaging, and it is perhaps surprising that SPECT has not been more widely adopted for lung scanning. Furthermore, with the widespread availability today of multidetector gamma cameras and improved computing power allowing faster processing, lung scintigraphy is ideally suited to SPECT acquisition.

How to Optimally Perform V/Q SPECT

SPECT can be used to image both ventilation and perfusion, however, this requires the use of appropriate imaging agents.

Ventilation

For imaging ventilation, several alternatives exist. These include inert radioactive gases such as ^{81m}Kr and ^{133}Xe, radiolabeled aerosols such as ^{99m}Tc-diethylene triamine penta-acetic acid (^{99m}Tc-DTPA), and the ultrafine carbon suspension ^{99m}Tc-Technegas.[19] Although the gases are considered to most accurately represent regional ventilation, several problems exist with their use. The use of ^{81m}Kr requires a krypton generator that is expensive and needs to be replaced daily. As a result, ^{81m}Kr ventilation imaging can be problematic to perform, especially outside of routine working hours. In addition, ^{81m}Kr gas must be continuously administered during image acquisition due to its short half life.[20] Although ^{133}Xe gas has the advantage of a longer half life, errors result from its recirculation due to clearance into the pulmonary circulation.[21,22] Given that SPECT assumes a static distribution of tracer for the duration of the data acquisition, these in vivo dynamics impair ^{133}Xe's ability to be used for SPECT ventilation imaging. Further compounding these issues, the lower energy of ^{133}Xe results in poorer spatial resolution, making it less than ideal as an agent to image ventilation.[20]

Given these limitations, ^{99m}Tc-labeled particulate aerosols such as ^{99m}Tc-DTPA or the carbon labeled nanoparticle ^{99m}Tc-Technegas tend to be more widely used due to their greater availability, low cost and good image quality.[20] Although the choice of agent depends on factors such as local availability, both have been reported to produce SPECT ventilation scans of good diagnostic quality. The most widely available is ^{99m}Tc-DTPA, which can be used with doses of just 0.8 mCi (30 MBq).[23] However, because of the relatively larger mean particle mass, problems may arise from central airway deposition, particularly in patients with chronic obstructive pulmonary disease. Technegas, with a smaller particle size, generally has greater alveolar penetration than ^{99m}Tc-DTPA. This results in less impaction in the central airways, with Technegas being demonstrated to have a similar distribution to that of an inert gas.[24-28] Together with its lack of lung clearance during image acquisition, this would appear to make Technegas an ideal agent for ventilation SPECT.

Typically, the doses of ^{99m}Tc-based imaging agents administered are identical to those used in conventional planar imaging, however, some authors have proposed a slight increase to the administered dose in an attempt to improve image quality.[29,30] In our institution, 13.5mCi (500 MBq) of ^{99m}Tc is added to a Technegas generator, with the aim of delivering a dose of approximately 1.35 mCi (50 MBq) to the patient. This equates to a posterior count rate of approximately 2.0 to 2.5 kcps.

Perfusion

As with planar imaging, ^{99m}Tc-macro-aggregated albumin (^{99m}Tc-MAA) is generally used to assess perfusion.[19] The distribution of MAA, which is proportional to regional blood flow, will be reduced distal to vascular occlusions in the pulmonary arteries. Thus, it can be considered that perfusion imaging performed in this fashion has an inherent "amplification," as even a small embolus can cause a large section of lung to be underperfused.

The dose of ^{99m}Tc-MAA used is dependent on the ventilation agent used. In the case where a radioactive gas is used, the dose of perfusion agent is typically lower than if a technetium-based ventilation agent is used. This is because the signal from the radioactive gas can be separated from that of the perfusion agent based on the energy level of the emitted photons. Additionally, in the case of ^{81m}Kr, the short half-life results in negligible gas remaining in the lungs during perfusion imaging. If a technetium-based agent is used for both ventilation and perfusion imaging, the typical approach is to "drown out" the underlying ventilation signal by administering a substantially greater dose of perfusion agent. A perfusion-ventilation dose ratio of $\geq$4:1 is generally required.[19] At our institution, the standard administered activity of ^{99m}Tc-MAA is 6 mCi (220 MBq), resulting in an effective radiation dose for the combined ventilation and perfusion scan of $\leq$2.5 mSv. Other authors have proposed the use of lower activity.[23]

Another approach to perfusion imaging is to use MAA labeled with a different radionuclide. Sanchez-Crespo and coworkers have used ^{111}In-MAA for perfusion.[31] By combining this with ^{99m}Tc-Technegas for ventilation, the authors were able to simultaneously acquire both ventilation and perfusion data. Although the limited availability and high cost of ^{111}In make this approach more expensive than ^{99m}Tc-based perfusion imaging, this approach has the advantage of reducing overall imaging time and producing inherently registered ventilation and perfusion image data.

Gamma Camera Hardware and Image Acquisition

To perform SPECT in an efficient fashion, multiheaded gamma cameras (either dual or triple head) are required. A typical protocol that uses a multiheaded camera requires 25 to 30 minutes of total acquisition time for a ventilation and perfusion dataset. Our acquisition protocol uses 3° radial steps over 360° with the ventilation study acquired for 12 seconds per projection and the perfusion study acquired for 8 seconds per projection. Other centers have reported adequate SPECT quality in as little as 6 minutes.[30] Although it is possible to perform SPECT with a single-head camera, the acquisition time becomes prohibitive for standard clinical practice. SPECT has the added advantage over planar imaging that multiple repositioning of the detectors and patient arms is not required, resulting in easier data acquisition for the technologist.

When using ^{99m}Tc radionuclides, low-energy, high-resolution collimators should ideally be used. These optimize image quality, although at the expense of reduced counts compared with low energy all-purpose collimator. If a higher-energy radionuclide such as ^{81m}Kr is used for ventilation, a medium energy collimator may be required. A matrix size of 128 × 128 (or greater) is appropriate for today's gamma cameras, although some reports have described using a 64 × 64 matrix with acceptable image quality.[29]

Image Reconstruction

Increasingly, iterative reconstruction techniques, such as the ordered-subset expectation-maximization algorithm (OSEM)[32] are replacing filtered back-projection in many areas of image reconstruction in nuclear medicine. These algorithms permit the inclusion of many physical aspects of the imaging process in the system model, such as attenuation, Compton scattering, and resolution degradation. Consequently, they offer better control of signal-to-noise in the event that a study is low in counts.[33] For V/Q SPECT reconstruction, we use an ordered-subset expectation-maximization algorithm (8 iterations, 4 subsets) smoothed with a postreconstruction 3D Butterworth filter using a cut-off of 0.8 cycles · cm^{-1} with an order of 9. Traditionally, corrections for photon attenuation and scatter are not routinely applied to V/Q SPECT, although they would be required for any quantitative analysis (eg, individual lobar function as discussed herein).

Image Display and Reviewing

After coregistration of the ventilation and perfusion data sets, the paired SPECT data are best viewed simultaneously in transverse, coronal, and sagittal planes. Although several computer software options exist that allow one SPECT study to be manually aligned with the other, some packages allow for automatic registration of the studies to each other.[34] Although images can be printed to film, given the amount of data to be considered, SPECT data are generally best reviewed directly on a workstation. This allows the reporter to interactively examine the linked ventilation and perfusion SPECT studies in each of the three orthogonal imaging planes. An example of a normal V/Q SPECT scan is shown in Figure 1.

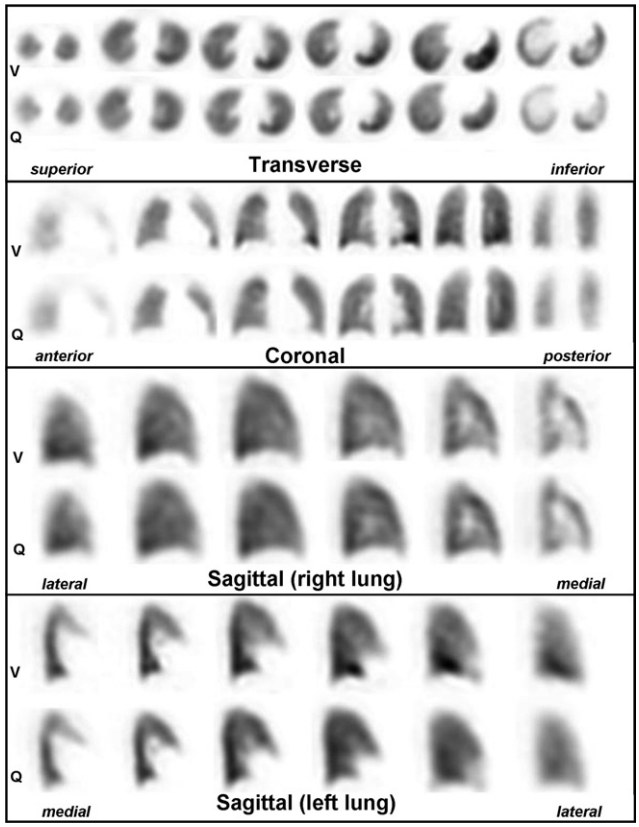

Figure 1 An example of a normal V/Q SPECT. Ventilation (V) and perfusion (Q) images (using Technegas and ^{99m}Tc-macro-aggregated albumin) are aligned and displayed in transverse, coronal and sagittal planes.

In addition to tomographic display of SPECT images, further data processing can also be performed. In the case in which ^{99m}Tc is used for both ventilation and perfusion imaging, perfusion data can be corrected for the background activity of the preceding ventilation scan using image subtraction of coregistered data sets.[23,35] Although this ventilation subtraction enhances perfusion defect contrast, it is not currently in routine use. The use of SPECT also facilitates novel ways of displaying V:Q quotient data to assist image reporting. Palmer and coworkers have described a technique where these images can be presented as either 3D surface shaded images or as tomographic sections in each of the orthogonal planes.[35] These so-called "quotient images" can be helpful in facilitating image reporting and are a useful way of demonstrating the location and extent of mismatched defects. Figure 2 shows an example of an abnormal SPECT study and corresponding selected V:Q quotient images in a patient with multiple PE.

How Does V/Q SPECT Compare With Planar Imaging?

The advantages of SPECT over planar lung imaging have been demonstrated repeatedly over many years. In a study performed 25 years ago in which subsegmental and segmental clots were induced in dogs, SPECT was shown to be more

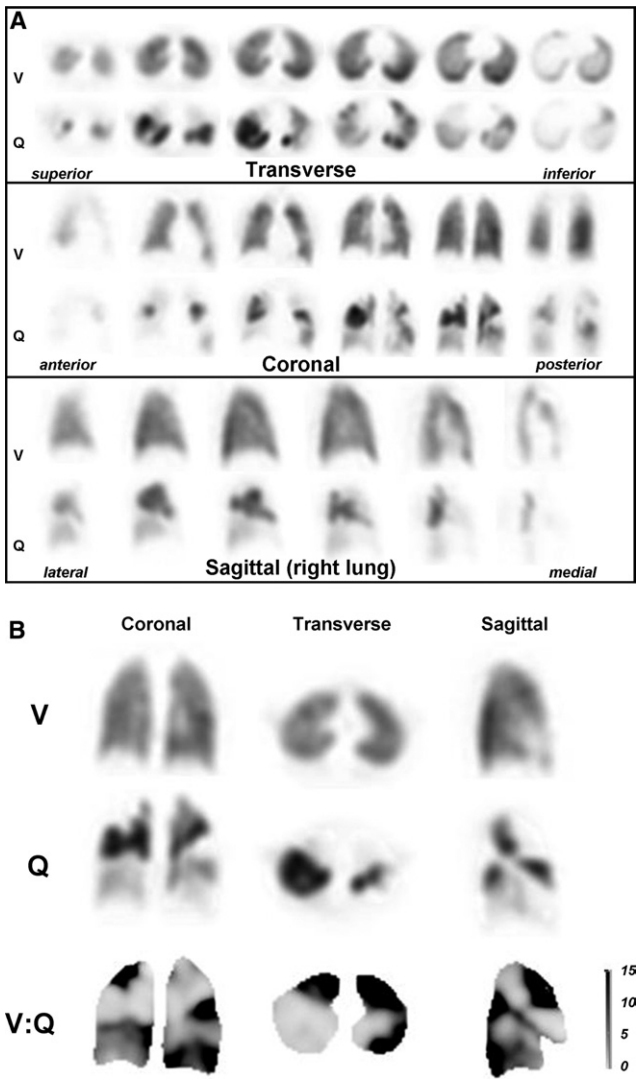

Figure 2 (A) Example of a patient with multiple bilateral PE. Ventilation (V) and perfusion (Q) images are aligned and displayed in transverse, coronal and sagittal planes. Multiple perfusion defects in areas with normal ventilation can be seen. (B) Representative coronal, transverse and sagittal ventilation (V), perfusion (Q) and V:Q quotient images from the patient shown in (A). Areas of pulmonary embolism correspond to dark areas on the V:Q quotient images, indicating a high V:Q ratio value.

sensitive than planar imaging.[36] Similar results were described by Bajc and coworkers,[37] who compared SPECT and planar imaging using ^{99m}Tc-DTPA aerosols and ^{99m}Tc-MAA in a porcine model. They induced artificial emboli labeled with ^{201}Tl and demonstrated SPECT to have an increased sensitivity (91% versus 64%) and specificity (87% versus 79%) over planar imaging. Using Monte Carlo simulation of lungs containing "deficits" to mimic PE, Magnussen and coworkers demonstrated that SPECT was more sensitive than planar imaging (97% versus 77%).[38]

Several other authors have investigated the performance of SPECT and planar imaging in clinical studies. In a study of 53 patients with suspected PE, Bajc and coworkers[23] found SPECT to be more sensitive than planar imaging (100% versus 85%). In addition, the authors concluded that SPECT demonstrated better delineation of mismatched defects, and less interobserver variation compared with planar imaging. Collart and coworkers, in a study of 114 patients, also demonstrated that SPECT was more specific than planar imaging (96% versus 78%) and had better reproducibility, both intraobserver (94% versus 91%) and interobserver (88% versus 79%).[39] Taken together, these data suggest that SPECT has a greater sensitivity and specificity, and improved reproducibility compared with planar imaging.

How Does V/Q SPECT Compare With CTPA?

Multidetector CTPA has evolved to the point in which it is frequently used as an initial investigation of patients with potential PE. Recent literature suggests that although it is highly specific, its sensitivity is somewhat less than desirable. With the multidetector CT scanners used in the large PIOPED II study, CTPA had a reported sensitivity of 83%, indicating that emboli were not detected in 1 in 6 patients.[40] Although the accuracy of CTPA appears to be high in cases in which the scan result is in keeping with the pretest clinical suspicion, this is not true of cases in which there is discordance between these results. CTPA, because of its anatomical nature, has an advantage of potentially diagnosing other pathology (eg, pneumonia or aortic dissection). However, this is at the expense of exposing the patient to increased radiation (something that is particularly concerning in the case of young women) and to the potential risks of contrast administration such as allergy or nephrotoxicity.

Unfortunately, little literature exists making a direct comparison between SPECT V/Q and CTPA. In 2004, Reinartz and coworkers[29] compared the performance of V/Q SPECT (using Technegas) with multidetector (4-slice) CTPA. In their series of 83 patients with a 45% prevalence of PE, they determined that SPECT was more sensitive (97% versus 86%) but less specific (91% versus 98%) than CTPA. Interestingly, however, both modalities had comparable overall accuracy (94% versus 93%). In 2007, Thomas and coworkers presented preliminary results of a prospective comparison of V/Q SPECT with CTPA performed using a 16-slice scanner in 100 patients with suspected PE.[41] They concluded that the overall accuracy of both examinations was comparable, suggesting that SPECT V/Q and CTPA could be used interchangeably.

Although further studies are needed to better examine the relative strengths of SPECT and CTPA in the same population, these data suggest that both SPECT and CTPA perform with similar overall accuracy. It appears that the strength of SPECT is its relatively high sensitivity, whereas the strength of CTPA is its relatively high specificity. Consequently, both SPECT V/Q scintigraphy and CTPA have a role in investigating patients with suspected PE. It is through recognizing the potential benefits and limitations of these two modalities that

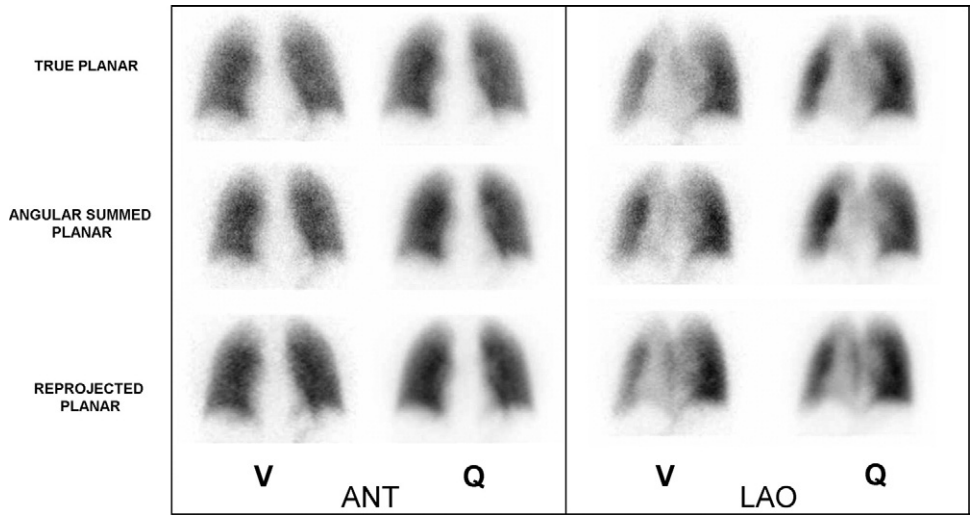

Figure 3 Example of true planar images compared with SPECT-derived angular summed images and reprojected images in a normal patient. For display purposes, ventilation (V) and perfusion (Q) scans are shown only in the anterior and left anterior oblique projections.

both V/Q and CTPA can be best incorporated into the diagnostic pathway of patients with potential PE.

How Should V/Q SPECT Results Be Reported?

The optimal way to report V/Q SPECT has yet to be clearly defined, and the supporting literature is sparse. Although the traditional way to report planar scintigraphy has revolved around the use of PIOPED probability categories, the adoption of these criteria to SPECT reporting seems inappropriate. This is particularly so, given that these criteria were derived using planar perfusion imaging and single view ^{133}Xe ventilation, a very different imaging technique to V/Q SPECT.

Reinartz and coworkers found that although the modified PIOPED criteria were generally applicable to SPECT reporting, counterintuitively, more patients had PE in the low probability category (64%) than in the intermediate probability category (50%).[29] Newer, and simpler, reporting criteria have also been proposed.[23,29,30] In the same study, Reinartz and coworkers[29] reported a high sensitivity (97%) and specificity (91%) using a simple reporting scheme that regarded all mismatches as PE. Other authors have also used alternative reporting criteria such as considering patients as positive for PE if they have more than 1 segmental or subsegmental mismatched defect[23] or if they have any clear-cut mismatched vascular-type perfusion defect, regardless of size.[30] When applied to SPECT reporting, these simplified schema have resulted in low rates of inconclusive studies (typically $<5\%$).[23,30,42,43] With its superior contrast resolution compared with planar imaging, SPECT will reveal small perfusion defects[29] and it remains to be determined how defects of this size are best reported. While further studies are needed to better define the most accurate reporting criteria for SPECT, our general approach is to regard segmental and moderate or large subsegmental mismatched defects as embolic (especially when multiple).

What New Applications Can V/Q SPECT Offer?

Generation of Planar Images From SPECT

For reporting specialists, viewing scintigraphic data in tomographic planes represents a significant change compared with traditional planar reporting. A good ability to relate image data to the underlying segmental lung anatomy is required, something that is helped by having access to an accurate lung atlas. During the transition phase to SPECT imaging, there may be a need for reporting clinicians to view both planar and SPECT data on each patient. Although the acquisition of both data sets can be performed, this approach significantly lengthens the acquisition time and may not be tolerated by many patients. Another approach is to generate "planar-like" images from SPECT data. Reinartz and coworkers[29] have described such a technique, which takes the acquired projection data from any point in a SPECT dataset and combines it with the frames obtained from the 1 or 2 projections either side of it. By summing these 3 to 5 data projections together (typically covering a 10° to 15° arc), "angular summed" planar images can be generated for any angle, including the traditional anterior, posterior, and oblique views.

Although this approach produces images that approximate the traditional planar images in most cases, images can be blurred and small defects may not be well visualized.[44] An example of this can be seen in Figure 3. An alternative approach proposed by Bailey and coworkers, is to use a reprojection technique. By forward projecting a reconstructed SPECT volume through a synthetic attenuation map derived from the lung SPECT emission data alone, planar images can be produced.[45] This technique has the advantage of producing images that use all of the counts from the SPECT dataset (typically 8-12 $\times$ 10^6 cts for each planar image), and can be used to produce planar-like images from any aspect. Although images generated with the use of this approach display subtle differences compared with traditional planar images, it has been shown that this has no significant impact on the final clinical interpretation.[44]

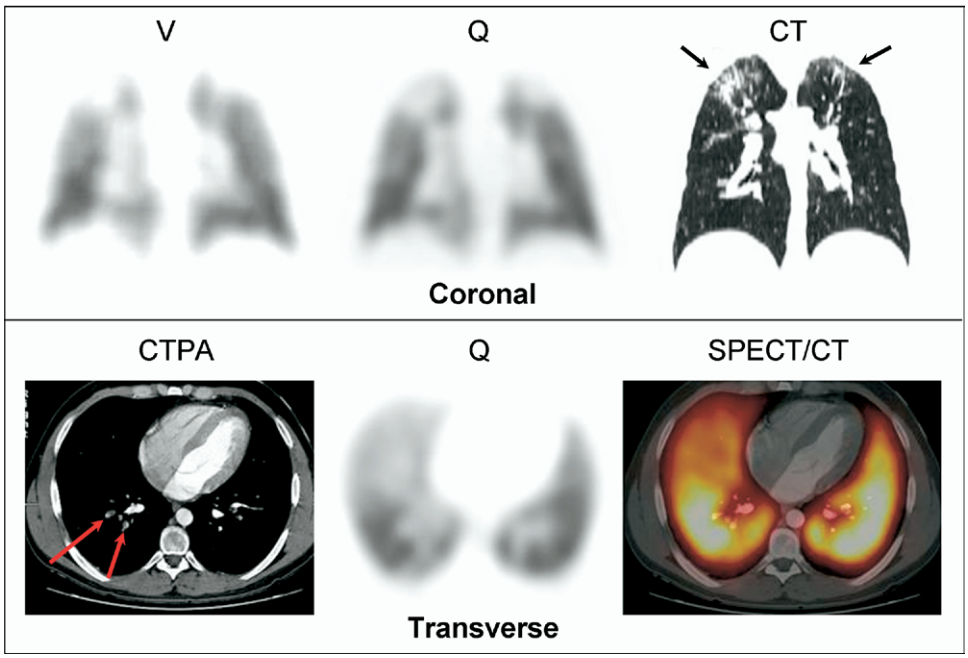

Figure 4 SPECT/CT fusion in a 36-year-old man with right chest pain, sarcoidosis, and bilateral hilar lymphadenopathy. Coronal SPECT images of ventilation (V) and perfusion SPECT (Q) show matched defects at the apices corresponding to the parenchymal opacities (arrowed) seen on the CT due to sarcoidosis. A CTPA performed to investigate potential PE demonstrated heterogeneous opacification of the right lower lobe pulmonary arteries (arrowed), and was considered to be inconclusive. The corresponding perfusion SPECT (Q) and fused perfusion SPECT/CT image demonstrated normal perfusion to this region, thus excluding PE.

SPECT/CT Fusion

Given the tomographic nature of both SPECT and CT data, the potential exists to combine the display of the images using image fusion. This can be achieved either by fusing data obtained from separate SPECT and CT scanners using software registration,[34] or by using data acquired in a single scanning session on a combined SPECT/CT scanner.[46] Reliable, accurate registration of the SPECT study and separate CT data using software fusion can be problematic due to differences in the scanning bed, arm positioning and breathing protocols. Greater registration accuracy would be anticipated with hybrid SPECT/CT scanners.[46] Some authors have postulated that SPECT/CT image fusion may be useful in cases of inconclusive CTPA imaging.[47,48] This approach may potentially combine the high sensitivity of SPECT with the high specificity of CTPA to improve the diagnostic accuracy of these investigations. Another option for combined scanners is to perform a "low-dose" CT study (typically using a 30-80 mA beam current) in conjunction with V/Q SPECT. This may provide anatomical information, such as vascular, parenchymal and pleural abnormalities, which may explain the cause of perfusion defects seen on the V/Q SPECT scan, thus altering the final SPECT interpretation and improving specificity (see Fig. 4).[49-51] In a preliminary study using software fusion of SPECT and CTPA in 30 patients with suspected PE, Harris and coworkers demonstrated the potential for reducing the nondiagnostic rate of V/Q SPECT scans using this approach.[47]

Objective Analysis

For many years, attempts have made to reduce the interobserver variability of V/Q scintigraphy by the use of objective analysis, rather than subjective image interpretation.[52-58] This has been problematic for planar imaging due to high levels of image noise, difficulties in image registration and poor spatial contrast.[59-61] SPECT has the ability to provide a more accurate determination of the ventilation and perfusion to each voxel which has been shown to correlate well with the traditional physiological measures of the pulmonary ventilation-perfusion relationship.[53,62]

In areas of normal lung, regional ventilation is closely matched to perfusion giving a ventilation-perfusion ratio close to 1. However, in areas of lung affected by PE, perfusion to the lung is typically impaired whereas ventilation remains largely unaffected, resulting in an increase in the ventilation-perfusion ratio. On this basis, Harris and coworkers have developed a methodology that determines the overall ventilation-perfusion histogram of the lung and then uses iterative curve-fitting to determine functional subpopulations of the lung likely to represent PE.[63] After applying this to a training population, objective measures of ventilation-perfusion heterogeneity were derived and applied to subsequent populations of patients with potential PE. This performed with impressive overall accuracy, achieving an area under a receiver operator characteristic (ROC) curve equal to 0.93. Furthermore, in a subset of 36 patients who had intermediate probability V/Q scans using traditional subjective interpretation, 86% were able to be reclassified as PE positive or PE negative, with an overall accuracy of 90%.[63] Given that PE is a disease where decreased perfusion is determined by the distribution of the underlying pulmonary vasculature, Harris and coworkers have further developed this methodology to allow objective analysis to be performed at a lobar level, rather than at a whole lung level, by using the anatomical information provided by SPECT/CT.[64] Objective analysis of SPECT scintigraphy has the potential to reduce the number of nondiagnostic scan results in PE diagnosis and may have applicability in other pulmonary disorders, such as asthma and emphysema.[63]

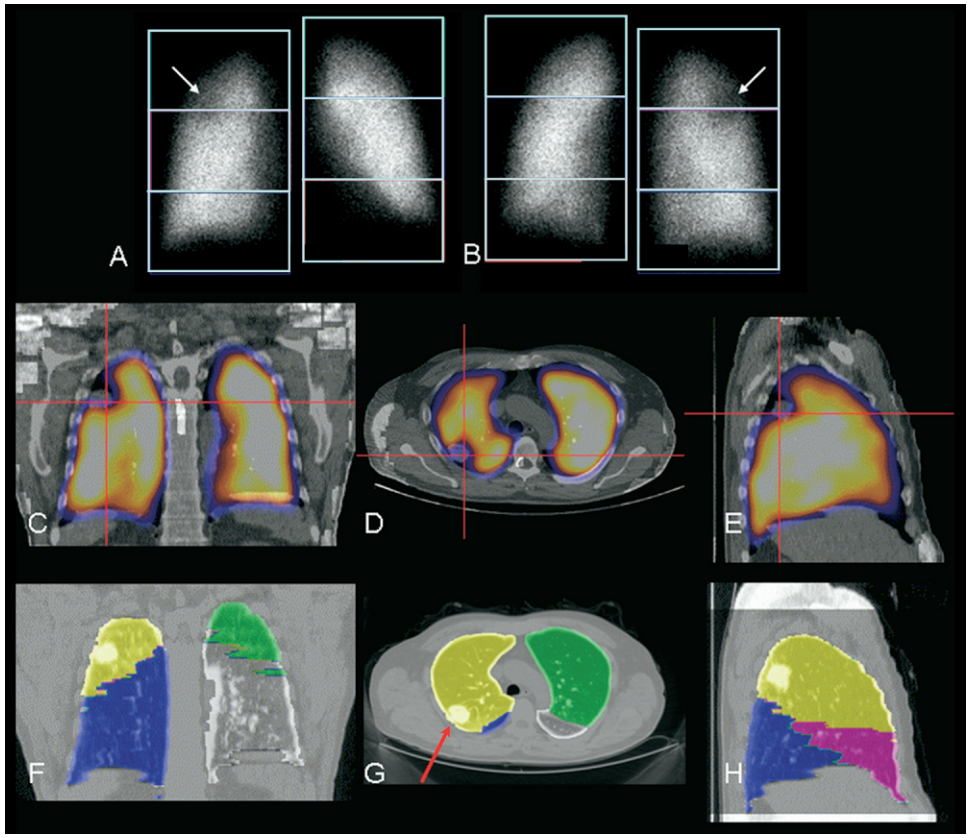

Figure 5 Anterior (A) and posterior (B) planar images in a patient with a right lung carcinoma (arrowed). The exact lobar location of the tumor cannot be determined on the planar imaging. Fused SPECT/CT perfusion images in the coronal (C), transverse (D), and sagittal (E) planes show the tumor and corresponding perfusion defect (indicated by cursors). Corresponding CT scan slices in the coronal (F), transverse (G), and sagittal (H) planes (with patient-specific lobar region-of-interest derived from the CT) shows the lesion to be located in the right upper lobe (arrowed). The SPECT/CT allowed accurate determination of each lobe's relative contribution to overall ventilation and perfusion.

Respiratory Gating

As SPECT data are acquired over minutes, during which time there is normal tidal breathing, respiratory motion results in blurring of the acquired data. One approach to overcome this is to use respiratory gating. This has been previously reported using both SPECT and PET data.[22,65] By only choosing data from a specific lung volume, it is suggested that the ability to resolve defects can be improved. Despite the potential advantages of this approach, to compensate for the use of only a limited portion of the total dataset, either a higher dose of radiotracer must be administered or patients must be scanned for a longer period of time. In addition, the implementation of respiratory gating is dependent on hardware issues, such as the need for a physiological respiratory synchronizer and list mode acquisition, which may not be generally available. Ideally, all of the data should be used but this will require sophisticated affine transforms of the lung shape during coregistration between different images captured at different phases of the respiratory cycle to "warp" it into one particular phase of the respiratory cycle.

Applications Other Than PE

Although the main clinical indication for V/Q scintigraphy is in the evaluation of PE, there are other indications in which SPECT may have an important role. For patients with lung cancer being evaluated for lung reduction surgery, it is useful to know the relative contribution to total ventilation and perfusion of the lobe(s) to be excised.[66] Planar V/Q scanning has been used for this purpose. However, because of the anatomical overlap of the lobes of the lung, this approach is inherently inaccurate. Neither of these limitations affects SPECT imaging. Furthermore, hybrid SPECT/CT scanners allow each lobe of the lung to be accurately identified and mapped back onto the functional data, thereby facilitating anatomically accurate assessment of individual lobar contribution to lung function[46] (see Fig. 5).

Other potential applications for the technique include guiding thoracic radiation treatment planning to avoid irradiating functioning lung, estimating regional lung function in patients with interstitial pulmonary disease, and using ^{133}Xe SPECT to assess obstructive lung disease.[22,67-71] Techniques such as fractal analysis as well as coefficient of variation of the pixel counts also have been used to objectively evaluate ventilation inhomogeneity with Technegas SPECT.[72-74] In addition, several authors have used SPECT imaging as a physiological tool to provide invaluable information regarding the regional distribution of ventilation and perfusion.[20] Given the relative ease with which these data can be collected and the power of the topographical information SPECT provides, this aspect promises to be an exciting emergent application for V/Q imaging.

Conclusion

Although it has been used in the diagnosis of PE for many years, it is evident that planar V/Q scintigraphy has some limitations. If the V/Q scan is to remain relevant as an imaging tool, it is important that it be optimized so that the diagnostic

information it provides is maximized. V/Q SPECT can be readily performed in most nuclear medicine centers today with no increase in patient imaging time. It has been shown to have superior sensitivity, specificity, reduced interobserver variability, and greater overall accuracy compared with planar imaging. Unlike CTPA, V/Q SPECT is not associated with contrast-related complications, such as allergy and nephropathy, a high radiation dose to the breast, or technical difficulties such as the need for a sustained breath hold or highly synchronized injection timing to acquisition. On the basis of the published literature, the accuracy of V/Q SPECT is similar to that reported for multi-detector CTPA. Furthermore, the higher sensitivity of V/Q SPECT makes it ideally suited to excluding potential PE. In the future, it is likely that V/Q SPECT imaging will be further improved by respiratory gating, image fusion and quantification. In addition, there are further emerging clinical and research applications that are likely to benefit from the use of V/Q SPECT.

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