Single photon emission computed tomography (SPECT)/computed tomography (CT): an introduction

Abstract Single photon emission computed tomography (SPECT) has been widely used in nuclear medicine for several decades. Since the late 1980s and early 1990s SPECT images have been combined with x-ray computed tomography (CT) to provide complimentary information of anatomy and function for improved diagnostic outcomes. Image registration emerged to bring SPECT and CT into a combined SPECT/CT imaging modality. Despite the success of these approaches, difficulties exist with the co-registration process; differing spatial resolutions, differing respiratory state / cardiac cycle and differing abdominal contents from examinations being performed at different times of the day. Hardware innovations, hybrid SPECT/CT, were developed to address co-registration software limitations. Acquisition of both SPECT and CT images can be made within a few seconds of one another. Since the first commercial system became available in 1999, which used low x-ray outputs with low quality CT images, SPECT/CT have evolved to utilise higher output diagnostic standard CT scanners such as 64 slice CT systems. The improved capability and diagnostic quality CT images has been accompanied by widespread clinical use and demand. The ability to accurately locate the functional information seen from SPECT has an incremental benefit over the SPECT and CT images alone. Clinical examples are provided to highlight these combined strengths. SPECT/CT is one example of the ‘blurring’ of traditional boundaries between radiology and nuclear medicine. An understanding of the technical and clinical aspects of SPECT/CT can provide improved clinical outcomes for the benefit of the patient and of the professional development of medical radiation scientists.

Keywords: SPECT, SPECT/CT, nuclear medicine, hybrid imaging.

Introduction

Single photon emission computed tomography (SPECT) is a nuclear medicine tomographic imaging technique that involves positioning the camera head at multiple angles around the body accumulating 180° or 360° of data at specific angular intervals, generally 2–6 degrees depending on the structure. The principle of data collection (Figure 1) and reconstruction is common with other tomographic techniques such as positron emission tomography (PET) and computed tomography (CT); traditionally, using filtered back projection with the more recent emergence of iterative reconstruction methods. SPECT is able to provide three dimensional (3D) information, typically presented as cross-sectional slices through the patient, which can be freely reformatted or manipulated as required.

Figure 1: Schematic representation of the principles of SPECT. Individual planar projections are acquired at regular intervals around the patient’s body (typically 60–120°) for either 360° or 180° degrees depending on the organ of interest. The subsequent image profiles are fed into the reconstruction algorithm (typically filtered back projection or iterative reconstruction) to reconstruct the object of interest. The reconstructed object generally suffers some loss of detail compared to the original object similar to CT or even a photograph.
In recent times, SPECT imaging has undergone significant advancement; multiple detectors, progressive digitalisation of the acquired signal, and higher count sensitivity. Perhaps the most significant advancement has been the development of hybrid SPECT systems with on board CT (SPECT/CT). The complementary nature of information provided by different imaging modalities is well understood in the medical radiation sciences. The registration of images from several modalities can provide a highly advantageous approach to identifying, correlating and quantifying regional changes in anatomy and function. It is only recent software and hardware developments that have enabled hybrid imaging to be exploited in the clinical setting.

**Image registration**

Image registration is the process of determining the geometric relationship between multiple imaging studies. The practical process of acquiring spatially (and sometimes temporally) correlated data from two or more imaging systems is complicated by several factors. These include images being acquired at different in-plane (X,Y) or axial (Z) spatial resolution, different slice thicknesses and such as the data being acquired on different days following unrelated protocols and at different locations. It is generally difficult to maintain the patient in a consistent geometry across separate imaging studies with respect to body position; consider the curvature of the spine and neck, location of the extremities, the shape of the patient table, the patient respiratory state and cardiac cycle, and the shape and status of the patient’s gastric, intestinal and urinary contents. Nonetheless, software has been developed that can effectively register and fuse images from multiple sources. Although accurate image fusion is relatively easy with the rigid structures in the brain and skeleton, it is more challenging within the thorax and abdomen. The problem of image co-registration is complicated when the images represent fundamentally different information (e.g. PET versus magnetic resonance imaging (MRI), SPECT versus CT) that may offer few commonly recognisable landmarks and are acquired at different levels of spatial resolution (Figure 2).

**Hardware/software fusion**

A measure of similarity between images is central to image registration. It determines the robustness and flexibility of the algorithm. A number of similarity measures have been suggested, generally falling into three categories: landmark-based measures, surface or edge measures, and voxel intensity measures. The early work on co-registration and fusion of images from the different modalities concentrated on the brain with success accomplished using external markers in head frames as reference points. Mathematical functions were soon added to correct for image distortions, and the algorithms were expanded into 3D. These techniques quickly evolved to the use of internal reference points. Image co-registration and fusion in the thorax, abdomen and pelvis, however, are more difficult because of physiological motion and lack of high-quality anatomic markers that can be visualised accurately by the different modalities. Problems are also created because of the difficulty in imaging the body in an accurately reproducible position with the different modalities, errors of at least a few millimetres are common. The inherent limitations of these techniques led investigators to explore options for developing new combined systems to improve the quality of image fusion. It was not until the late 1980s that significant progress was shown in the development of the SPECT-transmission scan technique. In 1987, Bailey, et al. at the Royal Prince Alfred Hospital in Sydney used a SPECT camera equipped with a planar transmission source of Gadolinium-153 (153Gd) (98 and 103 keV) to obtain simultaneous emission scans of Technetium-99m (99mTc) distributions and transmission scans. The transmission scan data were used to determine measured attenuation coefficients, thus providing a method for attenuation correction of the emission data.

**SPECT/CT**

In 1987, Mirshanaov proposed a combined x-ray transmission/emission system using separate detector systems to acquire data from a common...
improves the specificity of the scan. It is beneficial in the evaluation of imaging. The main advantage of SPECT is accurate localisation which and the CT system can operate as a stand alone multi-slice CT device but the manufacturers in developing commercial SPECT/CT products in use today (Figure 3). The SPECT system can operate as a stand alone SPECT device and the CT system can operate as a stand alone multi-slice CT device but the power of the system is in providing sequential data on the same patient.

SPECT provides several clinically important advantages over planar imaging. The main advantage of SPECT is accurate localisation which improves the specificity of the scan. It is beneficial in the evaluation of lesions in areas where the complexity of the structures can result in false-positive/false-negative findings on planar images. The 3D image reconstruction of SPECT allows separation of the overlying tracer accumulation from areas of interest, and, thus, also improves the sensitivity for lesion detection. While the planar and SPECT scans have ample evidence based clinical utility, the role of SPECT/CT is still being established in the clinical diagnostic algorithms. There are a number of key clinical applications that exploit the potential benefits of hybrid SPECT/CT:

Improved localisation of SPECT lesions. This is particularly important in SPECT studies with low count density or with highly specific radiopharmaceutical accumulation because there are few reference points for localisation. Gastrointestinal haemorrhage with labelled red blood cells (RBCs), Iodine-123 (123I) metaiodobenzylguanidine (MIBG) detection of pheochromocytoma, infection localisation with labelled white blood cell (WBC) are just a few examples.

Attenuation correction of SPECT data helps to remove artifacts associated with attenuated photons. This is particularly important from deeper structures and those non-uniformly affected by attenuation. CT based attenuation correction, for example, has made significant improvements to spine SPECT by providing improved definition of the anterior structures and limited attenuation as a cause of artifact in myocardial perfusion imaging.

The combined presence or absence of pathological changes observed on the CT in conjunction with the radiopharmaceutical uptake observed in SPECT can improve the diagnostic accuracy of the procedure. Classification of spine lesions as benign and malignant is one example. Plaque identification with myocardial perfusion SPECT is another.

Success with any of the above strategies will depend on the type of SPECT/CT scanner in use; the more rudimentary CT systems, designed for only the purpose of attenuation correction, or a full diagnostic multi-slice CT.

The first commercial system introduced in 1999 by General Electric Healthcare Systems used a low output, slow-acquisition CT scanner referred to as the Hawkeye, coupled with a dual-head scintillation camera. While this system has undergone several iterations since introduction, the underlying principle is the same; a standard multiple detector gamma camera is coupled to a low output (2.5 mA) CT scanner that shares the gantry with the scintillation detectors (Figure 4). While this provides a more than adequate capability for localisation of pathology and attenuation correction of SPECT data, an obvious disadvantage of this approach is that the CT system prevents configuring the detectors in a 90 degree cardiac set up. Perhaps the greatest marginal benefit of attenuation correction in SPECT is on myocardial perfusion imaging where attenuation artifacts (breast, bowel, diaphragm etc) can be differentiated from coronary artery disease. The 90 degree detector configuration has been a major advancement for cardiac imaging because it improves image quality and shortens acquisition time.

The third approach introduced by manufacturers in 2004 was to integrate commercially available diagnostic CT scanners with dual-head scintillation cameras (Figure 5). This provided genuine multi-slice (typically 8–64 today) CT options with variable tube currents (20-
500 mA), slice thicknesses of 0.6–10 mm, and rotational speeds of 0.5 seconds. These systems exhibit both good low contrast resolution and high contrast spatial resolution and, as such, are capable of producing images of quality sufficient to be used for clinical procedures.

Clinical utility

The cases below highlight the marginal benefit of CT in SPECT/CT imaging. Figure 6 is a 99mTc dimercaptosuccinic acid (DMSA) SPECT of the kidneys and highlights the limited localisation ability of SPECT when high specific tracer accumulation occurs. With the vast majority of radiopharmaceutical localising to the kidneys, other anatomic landmarks are difficult to determine. This will present some difficulties with accurate co-registration of SPECT and CT data performed on different devices.

Figure 6: CT (left), DMSA SPECT (centre) and fusion (right) images evaluating scarring in the kidneys.

Figure 7: CT (left), RBC SPECT (centre) and fusion (right) images for a RBC liver scan for the evaluation of haemangioma.

Figure 8: CT (left), sestamibi SPECT (centre) and fusion (right) images evaluating myocardial perfusion highlighting an incidental finding of a soft tissue tumour in the chest.

Figure 9: Corresponding sestamibi SPECT slices with CT attenuation correction (top) and without CT attenuation correction (bottom) highlighting the improved demarcation of CAD from artifact. In this case, the inferior wall demonstrates decreased perfusion suggestive of CAD which is shown to be attenuation artefact.
at different times but can be adequately managed by a dedicated hybrid SPECT/CT system. Figure 7 is a $^{99m}$Tc labelled red blood cell (RBC) SPECT of the liver to evaluate a potential haemangioma. The functional information is combined with the high resolution anatomic data to ensure lesion differentiation and localisation. Figure 8 is a $^{99m}$Tc sestamibi SPECT to assess myocardial perfusion with an incidental finding in the chest. The radiopharmaceutical also has affinity for soft tissue tumours and the CT data provides both accurate localisation and an evaluation of airways status. Figure 9 is a $^{99m}$Tc sestamibi myocardial perfusion SPECT study reconstructed with and without the CT based attenuation correction. The example highlights the role CT plays in differentiating coronary artery disease (CAD) from attenuation artifact. Figure 10 provides a liver / spleen study using $^{99m}$Tc colloid to identify an accessory spleen. The case demonstrates the nexus between anatomic and physiological information; each providing information crucial to final diagnosis. Figure 11 is a Gallium-67 ($^{67}$Ga) citrate SPECT study showing a liver abscess. The
Figure 14: A co-registered low dose CT has been used to show matching defects for the patient on the left image (low likelihood of PE) and a mismatched perfusion defect for the patient on the right image (high probability of PE).

SPECT again complements the CT in defining the function and anatomic distribution of the pathology. Figure 12 is a bone SPECT with a spine lesion. The addition of the CT study allows localisation and differentiation of the suspect pathology; benign versus malignant.

Localisation of the sentinel node is a crucial preparatory step in breast cancer surgery and lymphoscintigraphy plays a key role. Precise localisation of the sentinel node can be made by combining the highly sensitive nuclear medicine procedure and the high resolution CT (Figure 13). Under normal conditions the lungs are evaluated using ventilation and perfusion imaging when evaluating pulmonary embolism (PE). Normal ventilation with a perfusion defect is highly characteristic of PE whereas corresponding ventilation and perfusion defects are not. The CT study of the chest might provide sufficient detail regarding airways disease and, indeed, provide improved co-registration of perfusion and airways disease over the low resolution ventilation scan (Figure 14). There is certainly a role worth exploring for diagnostic quality CT angiogram (CTA) fused with perfusion SPECT to overcome the respective limitations of each to create a powerful diagnostic tool.

Low dose versus diagnostic CT

Figures 15 and 16 are pairs of images obtained on the same patient on the same day. The patient presented for a diagnostic CT scan and a bone scan. The CT scan was performed first and following whole body bone scanning a SPECT with low dose CT attenuation correction was performed. These circumstances afforded the opportunity to compare the low dose CT typical of attenuation / localisation SPECT/CT systems (in this case the GE Hawkeye 4) and the multi-slice diagnostic CT typical of many current SPECT/CT systems. It could be generally concluded that in these cases, anatomic markers were identified on each, despite the large difference in image quality. Certainly the additional anatomic definition of the multi-slice CT extends advantage to diagnostic decision making (as with the SPECT/CT cases above). That is, while the low dose ‘non diagnostic’ SPECT/CT systems provide a useful adjunct for localisation and attenuation correction, the more conventional multi-slice CT system integrated into a hybrid SPECT/CT system provides an incremental benefit for improved localisation, identification of incidental findings and assessment of pathology.
Conclusion

This overview provides an insight into technical and clinical issues in SPECT/CT; highlighting the role and importance of SPECT/CT. SPECT/CT fusion plays an important role in improving the diagnostic armamentarium across a diverse range of SPECT applications. Further research is required to better delineate circumstances where SPECT/CT provides a margin benefit with respect to diagnostic integrity.

References

8 Gnanasegaran G, Adamson K. Multislice SPECT/CT gains wider clinical acceptance:

```
Combined scans can improve lesion localization and characterization, as well as boost diagnostic confidence. *Diagnostic Imaging Europe* 2010; 26 (1). Available online at http://www.diagnosticimaging.com/cg/content/article/113619/1522547 [verified 8th July 2011].
```