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EDITORIAL

Innovative Design Concepts for Transmission CT in Attenuation-Corrected SPECT Imaging

Photon attenuation in cardiac SPECT is the major factor that contributes to quantitative inaccuracies when measuring in vivo distribution of radioactivity. The application of nonuniform attenuation correction significantly improves image uniformity of myocardial tracer distribution. In the article by Hollinger et al. (*1*), a compelling advancement in the technologic development of attenuation correction in SPECT imaging is presented. Hollinger et al. investigated the feasibility of using an asymmetric fanbeam geometry with a radioactive line source to acquire transmission CT (TCT) on a triple-head SPECT system to correct for photon attenuation in cardiac SPECT. What makes their work significant is that it provides a solution to the truncation problem that has slowed the acceptance of TCT with three-detector SPECT systems when simultaneously implemented with emission imaging (*2*).

The asymmetric fanbeam provides a means for obtaining truncation-free transmission images with a fixed line source not only for three-detector SPECT systems but also one- and two-detector SPECT systems. When only a portion of the field of view for a particular angular projection is covered, an individual projection can be completed by using the proper conjugate views from a 360° acquisition. The integration of TCT into SPECT systems has posed some challenges that have been the impetus for various innovative design concepts of which asymmetric fanbeam geometry is an important example. These developments also have led researchers to consider incorporating asymmetric cone-beam geometries in the design of future SPECT systems.

A variety of TCT design concepts have been proposed for commercial SPECT systems. The designers of these systems have struggled with numerous decisions, including whether to use sequential (*3–6*) or simultaneous transmission and emission (*7–11*) imaging; whether to use parallel (*3–7*), fanbeam (*6,8,11,12*), asymmetric fanbeam (*1,13*) or cone-beam (*14*) collimation; whether to use single-detector (*3–5*) or multiple-detector (*6,8*) systems; whether to use flood (*3,5*), scanning line (*7,10*), fixed point (*14*), single fixed line (*6,7,11,12*) or multiple fixed line (*15*) sources; and whether to use an x-ray tube (*16*) or gamma ray transmission sources (*1–15*).

In early work, the TCT study was performed before the emission study using a flood source mounted opposite a single, parallel-collimated detector (*3,5*). Unfortunately, this arrangement increased patient scan time, increased bulk and weight that was a result of the plane source and derived poor transmission statistics because of parallel collimation. Improvements were made by placing the transmission source at the focus of a converging collimator, such as a cone-beam or fanbeam collimator. However, the disadvantage of converging collimation is the truncation of transmission data that occurs with typical wide-field-of-view gamma cameras. A scanning line source with a parallel collimator reduces the truncation problem experienced with converging collimation (*10*). By electronically blanking the detector and zeroing in on the transmission energy, these systems can reconstruct distributions of narrow beam attenuation coefficients. However, the implementation by a motor-driven scanning line source and electronic blanking of camera electronics can be more complicated and more expensive than using a fixed line source. Parallel collimation also lowers the geometric efficiency and thereby requires increased source strengths that result in higher scatter-to-primary ratios and higher patient doses than occur with a line source placed at the focal line of a fanbeam collimator or a point source placed at the focal point of a cone-beam collimator.

Therefore, it is of particular interest to manufacturers to use a fixed source rather than a moving source. If a single, fixed, line source is used, then some type of fanbeam collimation is required. Using asymmetric or half fanbeam geometry, the truncation problem can be eliminated by assimilating projection samples over 360°. This means that a dual-detector system mounted with half fanbeam collimators placed orthogonal to each other can eliminate the truncation problem if each camera is rotated 180°.

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will propose the use of a scanning point source where a point source is scanned along the focal line of a half fanbeam collimator for application in simultaneous transmission and emission SPECT imaging (*17*). The half fanbeam geometry eliminates the truncation caused by fixed symmetric fanbeam systems. By scanning a point source along the focal line, this technique has the advantage of requiring lower source strengths than systems with fixed or scanning line sources. The only disadvantage is the complexity of mechanical scanning, which may be solved in the future using asymmetric cone-beam geometry with a fixed point source placed at the focal point.

The first commercial system to integrate TCT and SPECT is a three-detector system that positions a lightweight, low dose line source at the focal line of one of the symmetric fanbeam collimated detectors (*2*). This system enables simultaneous acquisition of transmission and emission data, without increasing patient scanning time, so that the reconstructed transmission map can be used to correct for photon attenuation in the emission reconstruction. The three detectors with symmetric fanbeam collimators are arranged in a triangle set with a transmission line source located at the focal line of one of the detectors and shielded in an assembly that moves in synchrony with the opposing fanbeam collimator. Data from transmission and emission sources at different energies are acquired by one detector, while the other two detectors acquire emission data. For example, a transmission source of ^{153}Gd is most often used with ^{99m}Tc-labeled radiopharmaceuticals and ^{57}Co is most often used with ^{201}Tl. Ideally, it is better to choose a transmission source with a photopeak energy lower than that of the emission source, such as a ^{153}Gd (99 keV) transmission source paired with a ^{99m}Tc (140 keV) emission source. When it is not possible to use a transmission source with less energy than that of the emission source, such as using ^{57}Co for the transmission source and ^{201}Tl for the emission source, it is important to keep contamination of the emission data to a minimum.

The triangular arrangement of a three-detector system presents a unique geometric configuration that uses short focal length (65-cm) fanbeam transmission geometry with detectors carefully positioned to avoid truncation of the incident transmission flux by the detectors adjacent to the line source. The system minimizes crosstalk between emission and transmission data energy windows, and any residual crosstalk between transmission and emission energy windows in all three detectors is corrected by algorithms that preprocess the projection data before reconstruction. However, because of the limited field of view (40 cm) of the fanbeam collimated detector, it is difficult to acquire fanbeam transmission data through the thorax without truncating the projections in most views.

A transmission maximum-likelihood (ML) iterative algorithm (*18*) is used to reconstruct the attenuation distribution, which is used in combination with an iterative ML-expectation maximization (EM) algorithm (*18*) to compensate for the attenuation of the projection of the emission distribution. The reconstructed attenuation map is scaled to the correct emission energy. The reconstructed attenuation distribution is used to calculate attenuation factors that are used to model the attenuation of the emission projection data as a large system of linear equations corresponding only to the data measured (no data extension is implemented to approximate the truncated data). This system is solved by using an iterative ML-EM algorithm to produce the attenuation-corrected radiopharmaceutical distribution. Even though transmission data can be significantly truncated, using iterative ML algorithms to reconstruct both transmission and emission data produces accurate (errors in the attenuation factors are generally 3% and in very few cases 10%) attenuation-corrected reconstructions of radiopharmaceutical distributions in the heart (*19*).

Attenuation factors are measured with sufficient accuracy for those factors that have the greatest influence on emission reconstruction in the myocardium. This is because the partial line integrals of attenuation coefficients are formed from ray sums that satisfy, in a least-squares sense, the measured projection data (*20*). The precision of the attenuation-corrected emission distribution is determined by the emission statistics for those levels of statistics commonly used in clinical applications (*21*).

Before the proposal of asymmetric fanbeam geometry (*1,13*), other transmission design concepts were considered for three-detector SPECT systems to alleviate the truncation difficulties of symmetric fanbeam geometry. One approach used a 30° slant-hole collimator with a scanning line source orthogonal to the axis of rotation (scanning along the axis of rotation) (*22*). In another approach, two scans were performed, shifting the patient to the left of the center of rotation and then to the right of the center of rotation, effectively increasing the field of view (*23*). The use of long focal length collimators for the transmission detector (such as 110 cm) also was proposed (*6*). Sequential transmission and emission scans were performed, and during the transmission scan, the detectors adjacent to the line source were pulled back to avoid truncating the incident flux. Also, by using computer simulations, it was demonstrated that an accurate definition of the body contour and patient bed shape significantly improved the image quality of the transmission reconstruction (*20*). This fact led other investigators (*24,25*) to use parallel collimators on the emission-only detectors when the scatter window was used to obtain information about the body contour and location and outline of the lungs.

Commercial manufacturers are grappling with the compatibility of TCT in future SPECT systems. Rotating dual, gamma-camera detectors that can be placed at right angles (90°) are currently the preferred camera configuration. This SPECT system offers the flexibility of performing whole-body bone imaging plus optimal cardiac imaging (detectors oriented at 90°).

Comparing the sensitivity between the dual-detector SPECT system and the three-detector SPECT system can be somewhat complicated. For the orthogonal two-detector camera, only 90° of rotation is required to obtain sufficient angular sampling of 180°. With a three-detector system, 120° of rotation will give a full 360° of angular sampling. The problem is that 180° of this, the posterior views, will be less sensitive than the anterior views due to attenuation. It is estimated that with the additional sensitivity of fanbeam collimation, both systems will have approximately the same sensitivity for the same resolution.

Other new, highly flexible multidetector SPECT system designs offer the option of selecting two detectors, three detectors or even four detectors to be mounted on the same gantry. The detectors can be positioned for a wide array of imaging needs, including opposed detectors for whole-body imaging, dual orthogonal detector arrangement (arranging two of the detectors at 90°) for cardiac imaging and triple-detector triangular arrangement for cardiac and brain imaging. These new systems also can perform central ray translation for better positioning of organs off the center of rotation. For these systems, the half fanbeam transmission geometry is appealing because transmission line sources can be more easily mounted to a multidetector

SPECT system when it is desirable for the detectors to stay close to the patient to achieve optimum resolution while simultaneously avoiding truncation of transmission beams.

The detectors in new commercial SPECT systems are wider, both in the axial and the transaxial direction, which makes the use of cone-beam geometry and other converging geometries appealing for imaging small organs like the heart. Specifically, for a three-detector SPECT system it may be desirable to combine fanbeam and cone-beam geometries. Then, a fanbeam collimator can be mounted on the simultaneous transmission-emission detector (with the transmission line source at the focal line, and cone-beam collimators can be mounted on the other two detectors (*26*). One advantage of this arrangement is that it solves the data insufficiency problem of planar circular orbit cone-beam tomography. Emission data from the fanbeam collimated detector can be used to fill in the missing data from the cone-beam acquired projections. On the other hand, a total cone-beam simultaneous transmission and emission SPECT system would offer the advantage of high geometric efficiency and reduction in transmission source strength requirements. New algorithm developments for half-cone-beam geometry solve the truncation problem and make the use of this technology in simultaneous transmission and emission SPECT systems very attractive.

Ideally, manufacturers would like to produce a system that does not require a transmission source and is capable of performing attenuation correction without having to perform a transmission study. There are several reasons for this. One reason is to eliminate the added complexity in hardware and software that is necessitated by the addition of transmission imaging. Another reason is that many hospitals are not licensed to handle high doses of radioactivity, especially amounts required for systems with scanning line sources. Also, it can be difficult to obtain line sources of uniform activity. The possibility of correcting for attenuation by inferring the attenuation distribution from only the measured emission data, by exploiting the fact that only certain attenuation distributions can be consistent with a given emission dataset (*27*), is very appealing. Simulations show that using consistency conditions derives attenuation-corrected emission distributions that are more accurate than when assuming a constant attenuation distribution (*28*). Another approach to accomplishing transmission-less attenuation correction is to use the intra-SPECT technique in which both emission and attenuation distributions are estimated simultaneously using an iterative reconstruction algorithm (*29,30*).

Recently, it has been demonstrated that the reconstruction of truncated projections can be improved using "knowledge sets" assembled from a patient population as a source of information to compensate for missing data in truncated transmission projections (*31*). The possibility of using these same knowledge sets to correct for attenuation without having to acquire any transmission data during patient examination is exciting. When reconstructing truncated transmission projections, the image quality of the transmission map and the emission quantitation is significantly improved with the addition of a known support of the outer boundary of the body.

The most important a priori information in CT is the knowledge of the location of the boundary edge, which in some applications can be truncated in several projection views. Therefore, one approach to obtaining body contour information in reconstructing truncated transmission projections is to use previous information in the form of a knowledge set of transaxial transmission reconstructions. The knowledge set would be obtained from TCT images of patients with anatomies similar to the "unknown" patient to be scanned. Preliminary studies show excellent attenuation-correction results obtained for both attenuation correction using truncated transmission projection and attenuation correction with no transmission data using a knowledge set of 1000 nontruncated TCT images obtained from positron transmission imaging. The use of consistency conditions and a knowledge set together might provide the best attenuation-corrected SPECT images, if a transmission-less approach is pursued.

Since the introduction of TCT into SPECT systems, it has been demonstrated that attenuation correction improves the sensitivity and specificity of cardiac SPECT lesion detection (*32*). Attenuation correction reduces the attenuation artifacts caused by the breast and the diaphragm. However, the development of attenuation-correction methods has shown the necessity to correct other physical effects of scatter and geometric point response. The correction for any one of the physical factors can accentuate the effect of the others. For example, because of the location and the prominence of liver uptake, attenuation correction can produce an overcorrection in the inferior wall of the left ventricle due to increased scatter from the liver to the myocardium (*33,34*). Additionally, there are clinical examples in which the partial volume effect is worse in the apex of the left ventricle after attenuation correction. It is anticipated that in the near future several approaches will also be available to correct for scatter and geometric point response.

The newer SPECT systems with TCT offer the ability to simultaneously obtain emission and transmission data necessary to correct for the variable attenuation in the thorax when reconstructing the uptake of radiopharmaceutical distributions in the heart. This is a welcome development, because this problem has plagued cardiac SPECT imaging for years. The two-detector system will probably continue to be the most used SPECT system, but three-detector SPECT systems offer additional sensitivity by combining cone-beam collimation with multiple detectors.

In both of these systems, asymmetric fanbeam geometry offers the potential for avoiding truncation with both transmission and emission data. The extension of this concept to asymmetric cone-beam geometries offers the potential for eliminating truncation and reducing transmission source strength. The integration of TCT into SPECT systems has spurred the development of new interesting collimator geometries, transmission source arrangements and detector orbit configurations, of which asymmetric fanbeam geometry is one example. In addition, algorithms have been developed for reconstruction of data acquired with these new design concepts that are more accurate in correcting for degradation due to all aspects of the physics of the imaging detection process. These developments will continue to evolve and may include the development of half cone-beam geometries in future SPECT systems with TCT.

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