Abstract: The feasibility of acquiring PET transmission information after tracer injection was studied using ring and rotating pin transmission sources. A combined transmission/emission scan was acquired, followed by an emission scan, used to subtract the emission counts from the transmission/emission data. The ratio of emission count rate for FDG brain scans to transmission count rate is 50-100% for a 5-mCi ring source, less than 5% for a 5-mCi pin source. Windowing of the sinogram, which rejects most random and scattered coincidences, also eliminates most emission counts. The magnitude and effects of residual random and scattered coincidences as well as increases in variability from transmission/emission scans were studied. In addition, the results of combined transmission/emission scans for a high-contrast emission source distribution using ring and pin sources are described.

Introduction

Accurate attenuation correction is one of the most important factors in producing quantitative images for positron emission tomography (PET) [1]. While calculated attenuation corrections based upon skull/skin outlines are acceptable for some levels in brain imaging [2,3], many PET studies require a transmission scan. Ideally, the transmission scan should be performed before tracer administration, there can be a significant time between the transmission and emission scans during the tracer uptake period. One approach is to perform a transmission measurement after tracer injection, immediately following or preceding the emission scan. The emission counts contaminating the transmission measurement can then be subtracted to produce accurate attenuation correction factors. With a ring transmission source, however, the emission count rate along a central projection line is a significant fraction of the count rate from the ring. The correction factors would, therefore, be noisy and sensitive to errors in emission subtraction.

A method for performing transmission measurements with a rotating rod or pin source has been proposed [4] and applied [5]. From the exact knowledge of the position of the source as it rotates around the patient aperture, the scanner electronics can window out coincidences which are not colinear with the source position. We propose the application of the rotating pin source to transmission measurements acquired after tracer injection. The sinogram windowing performed by the electronics will eliminate most of the emission counts as well as random and scattered coincidences. The remaining emission counts can be removed by subtracting emission data obtained from a conventional emission scan. Since the radioactivity concentration in the pin source is much higher than in a transmission ring, the emission counts are a much smaller fraction of the total counts, so that correction factors are less sensitive to errors in emission subtraction and show a smaller increase in variability.

Previous investigations into the feasibility of post-injection transmission measurements have been described [6] and are summarized briefly. Several measurements using ring and rotating pin transmission sources were performed. A combined transmission/emission (T+E) study of a phantom with regions of varying density, acquired using the ring source showed excellent agreement with a conventional transmission scan of the same phantom. However, a significant increase in variability in the attenuation data was observed. A transmission measurement of a patient after FDG injection showed poorer agreement between conventional transmission data and processed T+E data. The error was attributed to tracer accumulation between the emission and T+E scans which produced an inaccuracy in emission subtraction. A T+E study using a rotating pin transmission source was taken of a phantom with areas of different density and compared with conventional "pre-injection" ring transmission data. There was excellent agreement between attenuation correction factors obtained by the two methods of transmission measurement.

This paper will discuss the details of post-injection transmission scanning as developed with a rotating pin source simulator. It will examine the following aspects of this technique: magnitude and effect of residual random and scattered coincidences, accuracy of T+E scanning when applied to a non-uniform emission distribution, and increases in noise introduced by the emission subtraction.

Methods

All studies were performed on the Scanditronix PC1024-7B brain PET scanner, a tomograph with four rings (seven slices) of paired BGO/GSO crystals, a transverse spatial resolution (FWHM) of 5.0 mm, and a slice sensitivity of 20-25 kcps/μCi/cc.

Rotating Pin Source Simulator

A rotating pin source simulator (Figure 1) was designed and built at the National Institutes of Health to evaluate the feasibility of post-injection transmission scanning. This device is firmly mounted in the rear of the patient port of the Scanditronix PC1024-7B scanner. The arm extending out from the base plate holds a rectangular line source (1x2x15 cm) at the edge of the patient opening (30 cm diameter). By sequentially moving the control pin into each hole in the base plate, the source is reproducibly placed at 60 positions around the ring. An individual blank or transmission scan is performed with the source at each position. A complete scan is created by summing the sinograms after processing. The positions and size of the source were designed to ensure that counts are collected along all projection lines. The software developed for processing data from the rotating pin simulator mimics what is done in the electronics of an actual rotating pin transmission source. The simulator provided a useful tool for examining all aspects of rotating pin transmission measurements, details which could not have been as easily investigated with an actual rotating pin source.

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Processing of Rotating Pin Source Simulator Data

The following section describes the processing of the sets of raw data taken with the rotating pin simulator to produce transmission images. Each study, whether pre or post-injection, involves the acquisition of a set of 60 blank data sets at the 60 pin source locations followed by a set of 60 transmission data sets (conventional transmission or combined T+E). The first step in processing these data is to generate a sinogram for each data set (total 60 blank + 60 transmission sinograms) after deadtime correction but before subtraction.

Each blank sinogram is scaled for decay and will be attenuated during the transmission scan along the pin source activity. Hence, the bias in these factors resulting from accepted random coincidences will be much less than 3%.

Residual Random and Scattered Coincidences

While many random and scattered coincidences are eliminated by windowing the data to accept only coincidences collinear with the pin source, the non-negligible width of the pin [4,5], and therefore, the window, permits acceptance of some non-true coincident events. The residual randoms and scatter are depicted in Figure 2A and 2B, respectively, for the rotating pin simulator and Scanditronix PET scanner. Accepted non-true coincidences would produce quantitative errors (biases) relative to a conventional transmission scan with a ring source having randoms and scatter corrections applied. These effects were studied using a 20-cm cylindrical phantom uniformly filled with water as the source of attenuating medium.

Procedure: A single blank scan with the pin source (900 sec; 3.66 mCi F-18 at mid-scan time) at one location on the simulator was obtained. The cold phantom was then positioned and a single transmission scan (900 sec; pin activity had decayed to 3.26 mCi at mid-scan time) with the pin source at the same location was acquired. The procedure was repeated at a lower activity level in the pin source (970 µCi F-18 at mid-scan time for the blank scan and 820 µCi for the transmission scan) to reduce the effects of random coincidences and isolate the effect of scatter.

Data Processing: Individual sinograms were generated for the blank and transmission scans. The tails of a projection centered on the pin source were fit to a second order polynomial to estimate the magnitude of non-true coincidences contributing to the accepted counts within the sinogram window. Projections centered on the pin source are shown in Figure 3.

Results: The fraction of non-true coincidence counts were calculated for the blank and transmission sinograms at the two pin source activities. Scattered coincidences accounted for 4% of the counts within the window for a projection through the center of the 20-cm phantom. Random coincidences accounted for 2% of the counts in the window for 3.66 mCi in the pin source and <1% for 0.97 mCi pin source activity.

Discussion: The residual random fraction is proportional to the activity in the pin source. Therefore, for a 5 mCi source, approximately 3% of accepted counts (less for a smaller source size) will be accepted random coincidences. A 5 mCi source activity was chosen for the PET scanner used, based upon deadtime correction considerations. The attenuation correction factors are calculated from the ratio of blank to transmission counts along each projection. Random coincidences are the result of two singles from different segments of the ring striking detectors near their origin. The random fractions for blank and transmission scans will, therefore, be different, since the true rates will differ. However, in the case of the pin source, one single must cross the scanner to strike a detector far from its origin, such that the two singles making up an accepted random event are collinear with the pin source. These singles will be attenuated during the transmission scan along with the true coincidences, and the random fractions will be approximately the same for blank and transmission scans given the same pin source activity.

Hence, the bias in these factors resulting from accepted random coincidences will be much less than 3%. If the pin source activity changes between blank and transmission scans (e.g., physical decay), then the bias in attenuation correction factors may be sufficiently large to necessitate random correction.
A. Residual randoms coincidences. The accepted random count is produced by two single events which are colinear with the pin source. B. Residual scattered coincidences. The accepted scatter event is the result of small-angle scattering in the object such that the detected singles remain colinear with the pin. C. Residual randoms and scatter during a combined T+E study caused by the emission source. The additional random event is caused by one single from the transmission source and one single from the emission source striking detectors collinear with the pin source. The additional scatter count is the result of an emission event scattering in the pin source, such that the detected singles are colinear with the pin.

Scattered coincidences account for 4% of accepted counts (less with a smaller source size) for a 20-cm circular phantom. These residual events will lead to approximately a 4% underestimation of attenuation correction factors, since scatter is present only in the transmission scan and not in the blank data. This bias with respect to conventional ring transmission scans (assuming accurate scatter correction is applied to the ring data) may have undesirable effects when comparing data between PET centers, since a bias in attenuation correction factors will produce an error in quantification of emission values as well. To reduce this error, scatter correction of rotating pin source data may be necessary. One possible technique would be to window the filter function used in deconvolution techniques for scatter correction [7,8] to account for the electronic windowing being applied to the raw data.

The additional random and scattered coincidences introduced by the emission data during a combined T+E study are shown in Figure 2C. The random coincidences accepted in a T+E scan can be approximated by

\[
R_{T+E} = R_T + R_E + 2R_TR_E
\]

where \(R_T\) and \(R_E\) are the random coincidence rates caused by two singles from the transmission or emission sources, respectively, and the third term corresponds to random coincidences produced by one single from each source. The \(R_E\) rate is approximately the same as in the emission scan, and will, therefore, be subtracted along with the true emission counts during processing. For most PET studies, the count rate from the emission source is a small fraction of the count rate from the transmission source, so the third term will be small compared to \(R_T\). Since \(R_E\) is less than 3% of the transmission count rate, the additional random coincidences accepted will produce a negligible bias.

Additional residual scatter during a T+E study arises from scatter of emission counts by the pin source. Scatter of emission counts within the emission source itself will be subtracted along with the true emission counts.
counts during processing of the T+E data. Because the emission count rate along a projection accounts for a small fraction of the total count rate during a T+E study, and the probability of scattering in the pin source is also low (<10% for a 1-cm pin source cross-section), the magnitude of additional scatter accepted in a T+E study is negligible.

Non-Uniform Emission Distribution

While the previous work [6] demonstrated the feasibility of post-injection transmission measurements with a rotating pin source for low-activity FDG brain scans, the applicability of the technique to emission distributions containing a small hot region (e.g., active brain tumor, kidney) was less certain. In these cases, the high emission count rate along projections through the hot area might lead to increased noise and poorer quantitative accuracy relative to a conventional transmission scan. A water-filled 20-cm phantom containing a 5-cm cylinder was used to simulate those conditions. The radioactivity concentration ratio between the small cylinder and the background was 10:1. The measurement was made both with a ring source as well as the rotating pin source simulator.

Procedure: For the study with the transmission ring source, a blank scan was acquired (910 sec; 4.56 mCi F-18 at mid-scan time). The cold phantom was positioned in the gantry and a conventional transmission scan taken (710 sec; ring activity had decayed to 4.1 mCi at mid-scan time). The phantom was then filled with F-18 (680 µCi in the background; 340 µCi in the cylinder) and re-positioned in the scanner. A combined T+E scan was acquired (1140 sec; ring activity had decayed to 2.7 mCi at mid-scan time). The ring source was then removed, and an emission scan taken (1340 sec).

For the measurement with the rotating pin simulator, 60 blank scans were taken (15 sec each; 4.8 mCi F-18 at mid-scan time). The cold phantom was then positioned in the gantry, and 60 "pre-injection" transmission scans were acquired (13 sec each; activity in the pin source had decayed to 3.8 mCi at mid-scan time). The phantom was then filled with F-18 (580 µCi in the background; 340 µCi in the cylinder) and repositioned in the scanner. Sixty T+E scans were taken (19 sec each; pin activity had decayed to 2.7 mCi at mid-scan time). The pin source was then removed, and an emission scan acquired (1400 sec).

For both the ring and pin source scans, the scan durations were chosen to acquire approximately the same number of counts as would have been acquired during a 900 sec blank scan, a 600 sec transmission scan, and a 600 sec emission scan at the time the transmission source activity was 5 mCi. The emission activity levels were selected such that the concentration in the background was -0.2 µCi/cc at the time the transmission source activity was 5.0 mCi.

Data processing: The data processing of the ring T+E study involved the following steps. Sinograms were generated for the blank scan, the T+E scan, and the emission scan. Randoms and deadtime corrections were applied to all sinograms. The emission sinogram was scaled for decay and scan length to be comparable to the T+E sinogram and transmission data corrected for emission contamination were obtained. Finally, the transmission scatter correction was applied and transmission reconstructions performed. In addition, transmission data from the T+E study without emission subtraction were derived.

The processing of the pin studies followed the procedures described earlier in the Methods section (equations 1 and 2) with the exception that random coincidences were subtracted in the generation of the sinograms. Because the pin source decayed during the course of the measurements, the random rates were significantly different between the two sets of transmission scans and the blank scans, causing an error of 1% in the attenuation factors. With an actual rotating pin source, the radioisotope is long-lived (e.g., Ge-68), and the random fractions will not differ as much between blank and transmission measurements (see previous section). The transmission images resulting from these studies are shown in Figure 4.

Results: ROI analysis (1 3-cm region centered in the hot cylinder, 6 3-cm regions in background) of the ring source images showed percent differences (B-A) of +6.8±1.3% for the hot cylinder and -1.6±0.2% for the warm background. Without emission subtraction, the ROI percent differences (C-A) were -119±20% and -21±4% in the hot cylinder and background, respectively.

In the pin source images, the percent differences (E-D) were -0.2±0.8% for the hot cylinder and -0.4±0.2% for the warm background. Without emission subtraction, the ROI percent differences (F-D) were -13.2±0.8% and -2.4±0.2% in the hot cylinder and background, respectively. The difference in correction factors obtained using the pin source relative to those from the ring source is -4.8±1.8%. This bias is due in part to scatter in the pin data which is absent in the scatter-corrected ring data.

Discussion: The T+E study of the phantom with a hot region using the ring transmission source demonstrates the limited feasibility of performing post-injection PET transmission measurements in this manner. This approach is not ideal due to the sensitivity of the method to inaccuracies in emission subtraction. Quantitative transmission measurements require very accurate subtraction of the emission contamination, since the emission counts are a significant fraction of accepted T+E counts. An error in emission subtraction, such as was found in the patient T+E study [6], will introduce a bias to the final attenuation factors. In addition, extremely noisy transmission data (after emission subtraction) can produce over-estimates of attenuation factors due to the presence of the transmission data in the denominator of the calculation of these factors. For emission source distributions which contain localized hot regions, emission counts can account for most of the T+E data along projections through that area, and the attenuation factors are even more sensitive to errors in emission subtraction.

The pin T+E study and those previously described [6] show the feasibility of performing accurate post-injection PET transmission measurements with a rotating pin source with many emission distributions. Because the activity in the transmission source is more concentrated than in the ring, the ratio of emission to transmission counts is reduced, and there is little increase in variability in the transmission measurement. For FDG brain studies, where the emission distribution is uniformly of low intensity, large errors in emission subtraction due to changes in tracer distribution would have very small effects on the final attenuation data.

Noise

A potential limitation of post-injection transmission scanning is the increased variability in attenuation correction factors due to the emission subtraction. The magnitude of this effect will depend upon the relative contributions of emission and transmission counts to the T+E study as well as the emission source spatial distribution. While increased noise can be reduced by lengthening the transmission scan duration, it was desired to examine noise propagation in post-injection transmission studies under conditions typical of brain FDG imaging (15 min blank scan and 10 min transmission scan with 5 mCi transmission source activity; 10 min emission scan with 1 mCi phantom activity). The measurement described in the previous section was performed under these conditions. Although both the transmission source and the phantom activity decayed over time, their relative contributions to the T+E data remained constant, since both sources decayed with the same half-life. In addition, the scan durations were adjusted to ensure that the total number of counts collected was equivalent to what would have been acquired had there been no physical decay.

In the ring T+E study the pixel-to-pixel standard deviation increased by 22% (range 5 to 34%) in the 5-cm hot cylinder and 12% (2 to 20%) in the background relative to the T+E study as well as the emission source subtraction. With increased noise can be reduced by lengthening the transmission scan duration, it was desired to examine noise propagation in post-injection transmission studies under conditions typical of brain FDG imaging (15 min blank scan and 10 min transmission scan with 5 mCi transmission source activity; 10 min emission scan with 1 mCi phantom activity). The measurement described in the previous section was performed under these conditions. Although both the transmission source and the phantom activity decayed over time, their relative contributions to the T+E data remained constant, since both sources decayed with the same half-life. In addition, the scan durations were adjusted to ensure that the total number of counts collected was equivalent to what would have been acquired had there been no physical decay.

In the ring T+E study the pixel-to-pixel standard deviation increased by 22% (range 5 to 34%) in the 5-cm hot cylinder and 12% (2 to 20%) in the background relative to the "pre-injection" ring transmission study. With the pin source, there was no measurable increase in noise. The pixel-to-pixel standard deviation changed by 0% (-8 to +4%) in the 5-cm hot cylinder and 3% (0 to 5%) in the background relative to the "pre-injection" pin transmission study. In addition, the variability with the pin source data was found to decrease by 30% in the background relative to the ring source data.

Conclusion

We conclude that for many tracer methods, quantitative transmission measurements can be acquired with post-injection transmission scans using a rotating pin source. The bias in attenuation correction factors introduced by residual random and scattered coincidences when using a rotating pin source is small but still may necessitate correction. The additional bias produced by the emission source in T+E studies is, however, minimal. This technique has the added advantage of minimizing the likelihood of patient motion, thereby providing more accurate transmission attenuation correction factors.

References


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