# Reconstruction of Multiple Line Source Attenuation Maps

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*Abstract*

A simple configuration for a transmission source for single photon emission computed tomography (SPECT) is proposed, which utilizes a series of collimated line sources parallel to the axis of rotation of the camera. The detector is equipped with a standard parallel hole collimator. We have demonstrated that this type of source configuration can be used to generate sufficient data for the reconstruction of the attenuation map when using 8–10 line sources spaced by 3.5–4.5cm for a 30x40cm detector placed 65cm from the sources. Transmission data for a nonuniform thorax phantom was simulated, then binned and reconstructed using filtered backprojection (FBP) and iterative methods. It was found that optimum maps were obtained with data binned into 2–3 bins and FBP reconstruction. The activity in the source was investigated for uniform and exponential activity distributions. The effect of gaps and overlaps of the neighboring fan beams was also studied. A prototype of the line source system has been built and the experimental verification of the simulation results has started.

## I. Introduction

The potential of quantitative SPECT in medical diagnosis is widely recognized and is the ultimate goal of much research. In particular it is known that accurate attenuation correction is essential for quantitation of SPECT images and that it should be based on measured attenuation maps to account for the nonuniform distribution of the attenuating medium. These maps are also necessary for density dependent estimation of scatter distributions.

Over the years, several different configurations have been proposed for transmission source systems, the two most promising of which have been already introduced into clinics. These are a fixed line source with a fan-beam geometry, mostly used with triple head cameras [1], and a scanning line source for 90° dual head cameras [2]. Both these methods, however, have disadvantages. Truncation effects are inherent in the fan beam geometry and the scanning line source requires complicated electronic equipment to control its run-time operations. Also, in the case of the scanning line source the same activity is used to scan the whole range of tissue thicknesses present in clinical situations, therefore, the source must be quite strong in order to produce sufficient counts with large patients. A strong source may cause substantial dead time losses to occur at the edges of the detector, where the source illuminates only the periphery of the body and the attenuation is low.

Another method, which employed a set of four line sources mounted perpendicular to the axis of rotation, had only limited success due to suboptimal source geometry and a crude reconstruction method [3].

We have proposed [4, 5] a simple configuration for a transmission source which utilizes a series of collimated line sources (CLS) parallel to the axis of rotation of the camera. Important advantages of this geometry are that it does not require any complicated hardware and that it allows the activity distribution in the source to be tailored to the shape of the human body. The sources in the centre of the system illuminate the central part of the patient body where the attenuation is at its maximum, and can be given higher activity then those at the edges of the system where the attenuation is much lower. This design minimizes the amount of activity being used and the patient dose. The usage cost of the device is lessened, since stronger sources at the centre can be moved outwards as they decay, and only the central two sources need to be replaced.

The multiple line source is designed for use with a single head or a dual head 90° camera system where a source in its holder can be placed opposite to one (or even both) detectors without any restriction of the field of view of the detector. For simultaneous emission/transmission scans different isotopes should be used. Due to the special non-overlaping-fan-beams illumination of the object a 360° rotation is required.

We have demonstrated [4] that this type of source configuration can be used to generate sufficient data for the reconstruction of the attenuation map. Analytical simulations were performed for both uniform cylinders and chest phantoms using systems with 10–30 line sources. The optimum geometry for the transmission source system was determined based on the parameters of the standard SPECT camera. The resulting data

[1] We would like to acknowledge the support we have obtained from TRIUMF in designing and building of the collimators for the transmission source, Sophy Medical Inc. (now SMV International) for supplying us with the collimator frame to mount the prototype of the source, and Siemens Medical Systems for supplying us with the Gd-153 line sources.

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were analyzed using simplified "strip" and exact "fan beam" geometries and reconstructed with standard filtered backprojection (FBP) and with an iterative algebraic reconstruction technique (ART). The quality of attenuation maps obtained using both reconstruction methods were very similar with only minor artifacts present for the FBP approach.

In this paper we present the results of further simulation studies investigating the geometry of the transmission source and the accuracy of the attenuation map reconstruction. The artifacts caused by the existence of gaps between neighboring fan beams, as well as by their overlap have been investigated. Different levels of activity have been simulated for uniform and exponential activity distributions in the CLS system. The resulting transmission data have been preprocessed using different binning schemes and reconstructed with FBP, and iterative ART as well as conjugate gradient (CG) methods. Quantitative analyses of the resulting maps have been performed. The full account of the procedures which were used in data preprocessing and reconstruction will be outlined in a separate publication.

In parallel, a prototype of the transmission source consisting of six line sources has been built and the resulting fan beam profiles have been investigated. Transmission measurements of the Jaszczak phantom with air-filled spheres have been performed. The attenuation maps reconstructed using different binning and FBP are of the same good quality as our simulations results.

## II. Transmission Line Sources

The proposed CLS transmission source system consists of a series of highly collimated capillary tubes filled with activity. The whole system is mounted opposite to a detector equipped with a standard parallel hole collimator. The line sources are parallel to the axis of rotation of the camera. In order to minimize the number of line sources and optimize resolution we use a unique geometry. In the transaxial plane only half of the total area of the investigated object is illuminated at any time. Measurement of the complementary half is performed when the whole system has been rotated by 180°. This geometry requires that the line source system be located so that the axis of rotation of the camera is on the edge of one of the fan beams and that full 360° is scanned (see Figure 1).

A special collimator on each line source ensures that the radiation forms a fan beam which falls well inside the acceptance angle of the detector's collimator. The spacing between adjacent sources, the distance between the camera and the source system and the source collimation are all closely related and they are selected so that the fan beams illuminate the surface of the detector without overlapping. The collimation angle of the line source is defined as maximum angle between the direction of photons in the fan beam and the normal to the detector

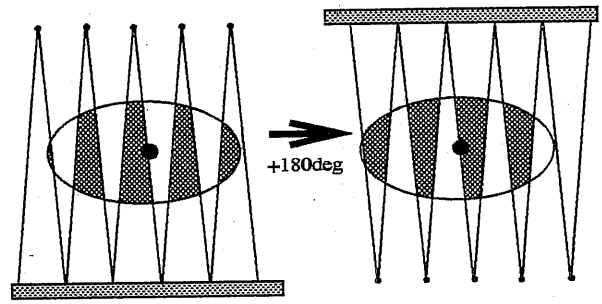


Fig. 1 Transmission source configuration; the dot indicates the centre of rotation of the camera.

surface. Since it is the source collimation which limits the width of the fan beams, any collimator with acceptance angle larger than the source collimation angle may be used on the camera. The geometry used in our studies permits the use of all parallel hole collimators which are currently available in our nuclear medicine department.

Small changes in the line source collimator settings, in particular increases in the distances between line sources, do not have any effect on the quality of the attenuation maps, providing that the widths of the fan beams created by the source collimator are appropriately adjusted. In particular, for the camera with a larger detector these distances may be increased and the number of line sources remain unchanged. Otherwise, a few extra line sources have to be added to ensure that the whole area of the detector is illuminated.

Our prototype source system allows for these changes, however, the final product will have the collimator fixed with all the distances adjusted to correspond to a particular size of the detector, the characteristics of the camera collimators and the camera type.

## III. Simulation Experiments

Our previous simulation experiments [4] indicated that our CLS system might, indeed, be used to generate good quality attenuation maps of patients. This work has been extended in the present study. The main objective of the simulation studies which are reported here is to model a more realistic geometry of the source and to investigate the resulting maps for accuracy and artifacts. The total activity required in the system and the distribution of this activity were studied together with the effects arising from gaps or overlaps of the fan beams originating from the neighboring line sources. Different binnings of the data prior to reconstruction were also investigated.

Based on our previous research, we used for these 3D simulations a system of 10 line sources. Each source was 16cm long with 3.5cm spaces between them. In our original design, 1mm diameter capillary tubes filled with activity were employed. However later, in our phantom experiments we have used 3mm Gd-153 rods. In order to investigate the issues related to the line source thickness and collimation we have performed a series of simulations using realistic 3D models of the two line

sources thicknesses. The collimator on each line source had a 3mm longitudinal opening. The length of the septa was chosen so that a maximum collimation angle was 1.54°. A detector with a field of view of 30x40cm was placed 65cm from the sources and was equipped with a standard high resolution parallel hole collimator with an acceptance angle of 3°.

Transmission data for a nonuniform "average man" 22x30cm elliptical thorax phantom was simulated with attenuation coefficients of $0.15cm^{-1}$, $0.02cm^{-1}$ and $0.20cm^{-1}$ in the body, lungs and spinal column, respectively. In some studies a phantom with only one 4.5x5cm cylindrical lung, a 2.5cm diameter spinal cord and three small lung-like spheres (with diameters of 2, 3 and 4cm) was simulated in order to generate maximum asymmetry in the data and the possibility of artifacts. Additionally, transmission data for a "large man" (with dimensions 30x40cm) was simulated to study the effect of low or missing counts in the projection data. In this last series of simulations the distances between line sources were increased to 4.5cm in order to illuminate the whole object and the source collimation was changed to 1.98°. Neither scatter nor septal penetration were simulated. In our simulation studies three topics were investigated.

## A. Activity of the CLS System

Contrary to the situation with other transmission source systems, the configuration of the CLS system allows for a nonuniform distribution of activity and the goal of the first stage of our study was to investigate and optimize it. In these tests the total assumed activity in the whole CLS system ranged from 600MBq to 5045MBq (16.4–136.4mCi). Two situations were studied: (i) this total activity being distributed uniformly between the 10 line sources and, (ii) the distribution of activity following an exponential function where the relative strengths of the sources were taken as: 0.301, 0.407, 0.549, 0.740, 1, 1, 0.740, 0.549, 0.407 and 0.301. An exponential distribution was used since it approximately accounts for the varying attenuation through the body. This has the added advantage that, as the sources decay, we can replace just the two central sources, shift the others outwards, and still retain the same distribution of activity.

## B. Gaps and Overlaps of the Fan Beams

Our next tests focused on the effects of gaps and overlaps of the fan beams. Since the real-world line sources have finite thicknesses the penumbra effect is always present. This means that photons originating from neighboring line sources mix, causing misidentification of events from the overlapping edges of the beams. Our approach to reconstruction of the attenuation maps relies on the exact identification of the origin of each detected photon, therefore gaps or overlaps may create significant artifacts. This effect was investigated using two approaches. In the first one we fixed the distances between the sources and changed the length of the septa on the line source collimators which, in turn, changed the widths of the fan beams. The studied fan beam configurations ranged from a 2cm overlap to a 2cm gap between the beams. In the second approach all the data were generated with 1cm overlap, but in the reconstruction the values of pixels in the overlapping regions were simply ignored, which was equivalent to having gaps. The first situation corresponded to hardware adjustments which can be made prior to an experiment, the second investigated the effects created by removing part of data which were already acquired with overlaps.

## C. Attenuation Map Reconstruction

In the last series of studies we investigated different reconstruction and data preprocessing techniques. The FBP, iterative ART and CG methods were used. Four different binning schemes were tested with projection data before reconstruction being binned into 1, 2, 3 and 4 bins.

Simulated data were initially generated in 1000 bins per projection to model continous count distribution. Before reconstruction they were rebinned into M bins, where M was the number of line sources used in the generation of a given data set multiplied by a *binning factor* of 1, 2, 3 or 4. Assuming that the reconstruction was performed using an N x N matrix (for example 128 x 128), the counts in each one of these M bins were uniformly distributed over k pixels, where k was defined as follows. For iterative reconstructions an exact fan beam geometry is used. In this case k was equal to N/M, the number of pixels covered by each fan beam. For the filtered backprojection method the pixels which were considered in a projection corresponded to a strip with width equal to half that of a fan beam. Thus k was equal to N divided by 2M and only half of the pixels were filled with counts from this projection. The complementary data for the other half were obtained from the opposite projection. Only after this data pre-processing (binning) was performed the logarithms of the count ratios were calculated and then reconstructed using FBP or iterative methods. For further explanation of FBP binning see Figure 2.

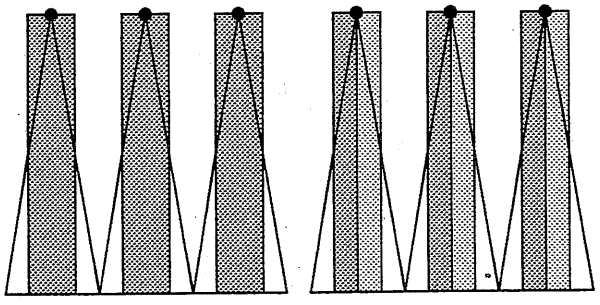

Fig. 2 Initial data binning for backprojection reconstruction. Data produced in fan beams are approximated by a series of parallel strips.

## IV. Phantom Experiments

A prototype transmission source has been built and experimental verification of its performance begun. At present, the whole system consists of only six line sources with lead collimators. In order to make the collimator lighter and also more flexible for the development studies it has been divided into two parts, A and B (Figure 3).

Each line source is placed between the two strips of lead, with adjustable separation, which together constitute part A of the collimator. The second part, part B, has a fixed opening of 3mm. It can be moved relative to the part A. Also, the distances between the line sources can be changed. Part A acts as a pre-collimator directing the radiation into part B, which is responsible for the final formation of the fan beam. The overall collimation angle can be changed by altering the distance between parts A and B.

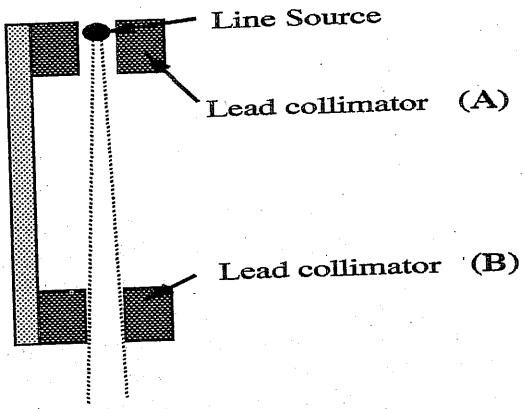


Fig. 3 A schematic drawing of one of the line source collimators. The distance between parts A and B of the collimator is adjustable, as is the distance between the lead strips in A part B. This allows the use of line sources with different diameters. The opening between the lead strips in part B is fixed at 3mm.

Our transmission line source system may be used with a single head cameras for dual isotope or sequential imaging or, one or two CLS systems can be mounted on dual head 90° cameras opposite to one or both heads. At the present stage of testing, we are using a simplified configuration of the system and a dual-head flexible angle DST Sophy camera. In this preliminary form, the system is mounted on an old collimator frame. This allows us to place it on one detector (disabled, and used only as a support for the source), while the other detector is used for imaging. The detectors are positioned at 180° to each other and the maximum distance between them is 65cm.

In our phantom experiment we have used 3mm thick and 16cm long Gd-153 rods (the actual source thickness used inside each rod was 1.5mm). The activities of the sources used in our experiment were 82, 140, 167, 167, 140 and 82MBq. In order to illuminate the whole 22cm diameter object in our transmission experiments the distances between sources were set to 4.5 cm with the source collimation adjusted accordingly.

In this first experiment, the fan beams were just touching each other, however the events from the penumbra created a small overlap of less than 1cm, similar to this seen in Figure 4b. The camera was equipped with a low energy high resolution collimator (LEHR) with an acceptance angle of 3°. A plastic cylinder 22cm diameter and 21cm high, filled with pure water and containing six co-planar plastic spheres filled with air with diameters ranging from 1cm to 3.5cm was imaged. The 128x128 matrix was used and a total of 128 projections were acquired over 360° rotation. In both scans, with and without the object, a time of 20s per projection was used.

## V. Results and Discussion

### A. Simulation Studies

A realistic 3D model of the line sources and the collimator was used in the studies of the effects related to the line source thickness. The simulated profiles of the fan beams obtained with 1mm and 3mm line sources both spaced by 3.5cm are presented in Figures 4a and b, respectively. Both simulations were designed to generate the same 0.5cm overlap of the fan beams. In order to achieve the same 4.0 width of the fan beam on the detector surface the collimation of the line sources had to be adjusted appropriately. This collimation in the case of the thicker source is more restrictive, resulting in a narrower beam and also a lower number of photons passing through the source collimator. The fan beams generated by the sources with 1mm diameter have more counts, are broader but also have sharper edges. Less penumbra effect is observed. The clear conclusion which can be drawn from these simulation tests is that it would be beneficial to use narrow line sources in the CLS system. Our phantom experiments have confirmed these findings.

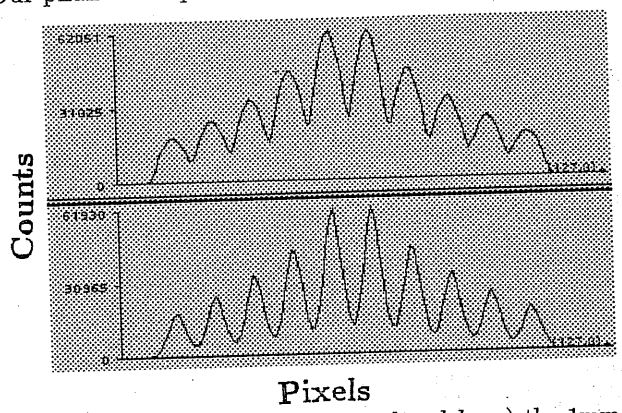


Fig. 4 Profiles of the fan beams produced by a) the 1mm and b) the 3mm line sources spaced by 3.5cm.

Photons originating from the line sources form a series of narrow fan beams, allowing two approaches to attenuation map reconstruction, one based on a "parallel-strip" geometry and the other on a "fan-beam" geometry [4]. These approaches were used for standard FBP and iterative reconstructions (ART and CG),

respectively. All reconstructions were performed in 2D.

Initially, for the FBP reconstruction the data originating from each line source were binned into just one strip, but this caused artifacts [4]. We have investigated different binning schemes and have since found that multiple bins give much better map reconstruction with two bins being the optimum. More than two bins are appropriate for the high statistics data, but for low activity sources they result in greater binning error and produce unsatisfactory maps. Similar studies for the iterative reconstructions demonstrated that, here also, two or three bins are optimum. Figure 5 presents an estimate of the error between the true and the reconstructed values of the attenuation coefficients $\mu$ calculated for different binning schemes using FBP and ART methods.

The error was estimated as:

$$\text{Error} = \sqrt{\frac{\sum_i (\mu_{true} - \mu_{rec})^2}{N}} \qquad (1)$$

where: $\mu_{true}$ and $\mu_{rec}$ are the true and the reconstructed values of the attenuation coefficients summed over all N pixels of the object. The reconstructed maps and the results presented in Figure 5 show that both reconstruction methods work almost equally well. The optimum maps were obtained for FBP with data binned into 2 bins and for ART with 2 or 3 bins and about 7 iterations. The results for the CG method were similar to those obtained when using the ART method.

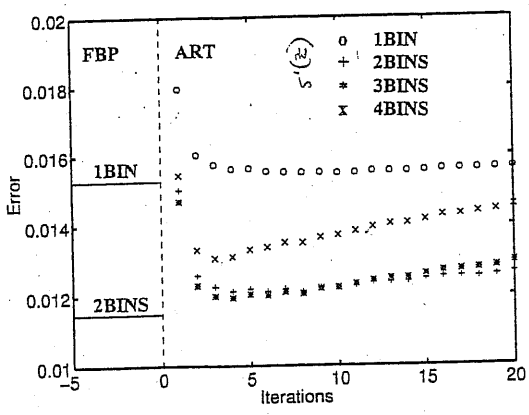


Fig. 5 Error in the reconstruction of the attenuation map using different binning with FBP and ART.

The conclusion from these studies is quite clear. Reconstructions using the iterative methods required longer computation times than the FBP approach, but did not provide better quality maps. In fact, as can be seen from Figure 5, maps created using the FBP method had smaller errors. Therefore, in all subsequent studies we binned the data into 2 bins and used FBP to reconstruct attenuation maps.

The results of simulation tests of source activity performed for the "average man" model are summarized in Figure 6. The errors between the true and reconstructed values of the $\mu$ were the lowest for the transmission

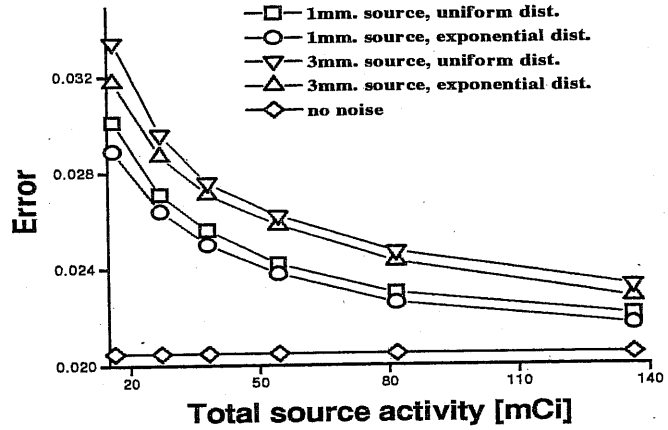


Fig. 6 Error in the reconstruction of the attenuation map using different source activity distributions for 1mm and 3mm thick lines.

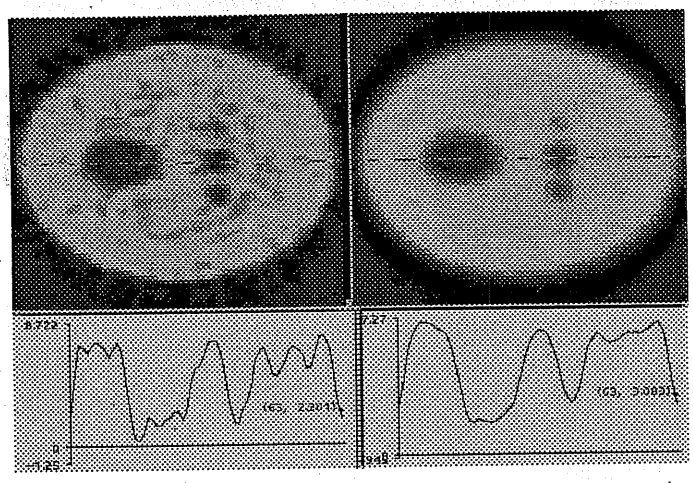

Fig. 7 Attenuation maps for the "large man" model using the line sources with total activity of 2035MBq with a) no smoothing, b) with smoothing.

source composed of 1mm thick lines with exponential activity distribution. Analysis of the same figure shows that measurement using a non-uniform activity source will generate a better map than when the same total activity is used in a uniform source. This effect is more pronounced for the case of "large man" model, since for larger, more attenuating objects the missing counts in the centre of the system become more important.

An important feature of the CLS system is the method used for map reconstruction. The fact that the data are binned before reconstruction substantially reduces the statistical noise in the data and minimizes the missing counts problem. Good quality maps can be obtained for large objects even with relatively low activity in the transmission source. Figure 7a presents an example of such attenuation maps for the "large man" model obtained with 2035MBq (55mCi) total activity in the CLS system. The quality of the reconstructed map can still be improved by smoothing the transmission data before

reconstruction. The effect of applying a 3D Gaussian smoothing function is presented in Figure 7b.

The last part of the study was concerned with the effect of possible overlap or gap between the fan beams originating from the neighboring line sources. This problem was studied extensively for different phantom configurations and source activities. As discussed previously, the results of two approaches to overlap creation were investigated. An example of this effect on the attenuation maps reconstructed using 2 bins and FBP method is presented in Figure 8. The results of these tests demonstrated that an overlap creates much more pronounced artifacts than a gap of the same size. This is an important point to consider when designing the hardware and analyzing the data. No difference has been observed between maps reconstructed from data with gaps generated by the two approaches.

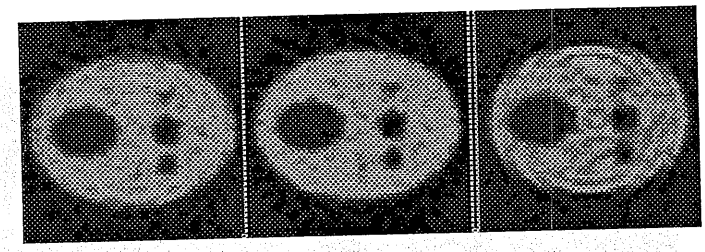

Fig. 8 Attenuation maps reconstructed using the FBP method with 2 bins; a) 1cm gap, b) 0.5cm gap, c) 1cm overlap. The data were created with 1cm overlap. The total activity in the source was 2035 MBq.

### B. Experimental results

The results of the first experiment performed with our transmission source are very promising. The experimental data contained some overlap and were reconstructed using three different methods. In the first reconstruction the data were only binned into 2 bins and reconstructed, without any smoothing, using the FBP method. In the second and third reconstruction, prior to binning, they were preprocessed using our second approach, meaning that the pixels in the overlap region were ignored creating a 0.5cm or 1cm gap. Figure 9 presents the reconstructed maps for these three cases a) with overlap and no preprocessing, b) with 0.5cm gaps and, c) with 1cm gaps.

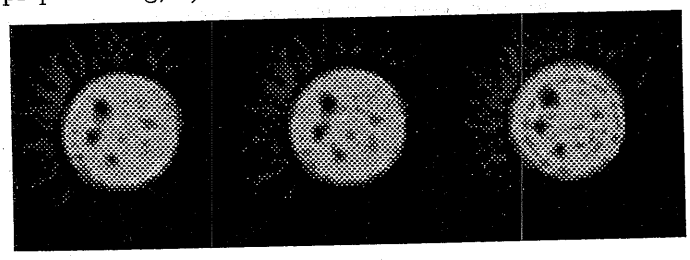

Fig. 9 Experimental attenuation maps reconstructed using the FBP method with 2 bins; a) no preprocessing, b) 0.5cm gap, c) 1cm gap created by ignoring counts in the overlaping region.

The experimental results confirm our previous findings, that the small gap between beams does not create any significant artifacts and can be used in clinical situations to remove those caused by the data overlap. The final attenuation maps do not display any major artifacts except those due to statistical noise in the data which can be partly removed by smoothing. The diameter of the smallest sphere which can be seen is equal to 2cm, as was predicted by simulation studies.

## VI. Conclusions

The results of our simulation tests of multiple line sources for transmission measurements in SPECT are very encouraging. The attenuation maps reconstructed using the FBP exhibit only very minor artifacts provided that the data from each line source are binned into two or three bins before reconstruction. No significant improvement was found by using iterative reconstruction methods, and FBP was identified as the method of choice based on its speed and simplicity.

The minimum total activity required in the source has been found to be about 1800MBq (45-50mCi) for an exponential activity distribution. If a uniform distribution is used, higher activity (2200MBq) would be needed to produce the same map quality.

Overlap of fan beams creates more artifacts than gaps between them. In fact, by using a small 0.5cm gap between fan beams, we could generate good quality attenuation maps from both simulated and experimental data which were generated with 1cm overlaps.

A prototype consisting of the six line sources has recently been built and experimental verification of the results of our simulation studies has started. The resulting attenuation maps confirmed our simulation results and indicated that a collimated line source system can be developed for clinical use.

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