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Characterizing the contribution of cardiac and hepatic uptake in dedicated breast SPECT using tilted trajectories

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Abstract

A small field of view, high resolution gamma camera has been integrated into a dedicated breast, single photon emission computed tomography (SPECT) device. The detector can be flexibly positioned relative to the breast and image beyond the chest wall, allowing the system to capture direct views of the heart and liver. The incomplete sampling of these organs creates artifacts in reconstructed images, complicating lesion detection. To understand the limits imposed on a 3D acquisition trajectory, sequential tilted trajectories at increasing polar tilt are utilized to collect data of anthropomorphic phantoms filled with aqueous ^{99m}Tc in a clinically realistic concentration ratio. The counts collected per projection between different scans and the SNR, contrast and resolution (FWHM) of two hot lesions were compared. As expected, the counts per projection increased when the camera had direct views of the heart and liver, but remained relatively constant at other angles. The SNR, contrast and FWHM were more affected by the insufficient sampling of the data by the large polar angles than by the cardiac and hepatic activity. An upper bound on polar tilt for each azimuthal position reduces the artifacts in the reconstructed images. Such trajectories were implemented to show artifact-free reconstructed images.

1. Introduction

Single photon emission computed tomography (SPECT) has numerous applications for imaging functional processes throughout the body by directly measuring the gamma rays emitted by an injected radionuclide labeled to a molecule which is incorporated into the body (Phelps 1977). One such radiotracer, ^{99m}Tc methoxyisobutylisonitrile, was originally developed for cardiac studies (Santoro *et al* 1988, Savi *et al* 1989, Taillefer *et al* 1989), but subsequently found to be readily taken up in breast cancer (Maublant *et al* 1996, Scopinaro *et al* 1994).

Initially, with large whole-body cameras, planar and SPECT nuclear medicine studies found that breast lesions smaller than 15 mm could not be reliably imaged, limiting its clinical usefulness (O'Connor *et al* 2007, Tofani *et al* 1999). But with developments in camera detector technology, specifically those with smaller fields of view (FOVs) (Tornai *et al* 2005a), the sensitivity for sub-centimeter lesions significantly improved (Brem *et al* 2005, Hruska *et al* 2008, Spanu *et al* 2007) making dedicated breast imaging more practical. Several planar dedicated breast imaging systems have been developed with these types of

detectors (Brzymialkiewicz *et al* 2005, Brem *et al* 2008, Hruska *et al* 2005), but only one to our knowledge is a clinical SPECT system (Brzymialkiewicz *et al* 2005).

The relatively large uptake of the radiotracer in the heart and liver and close proximity of these organs to the breasts can potentially contaminate or degrade the breast image (Williams *et al* 2003). For imaging systems that orient the detector face parallel to the breast's central axis (nipple to the chest direction, as in a cranio-caudal view), these organs have only posed minor contamination to the imaging studies (Wang *et al* 1997, Hruska and O'Connor 2008) but also resulted in viewing a truncated breast volume in the image. Use of slant-holed collimators angled toward the chest is possible to improve this condition, but would consequently result in an increase in torso contamination in the breast images. Our fully flexible SPECT system, which can contour along the surface of a breast, has the ability to image into the chest wall resulting in imaging a greater volume of the breast. However, contoured tilted trajectories also potentially contribute background signal contamination from the heart and liver, in spite of the superior energy resolution capabilities of high-Z and density, compound room-temperature semi-conductor detectors coupled with appropriate collimators (Archer *et al* 2003, Brzymialkiewicz *et al* 2006, Tornai *et al* 2003).

Although there are numerous (if not infinite) possible acquisition trajectories which could be created for tomographic data acquisition with such a flexible SPECT system, trajectories were originally created heuristically for use in our lab (Archer *et al* 2003, Brzymialkiewicz *et al* 2006), based on generally satisfying volume sampling criteria (Orlov 1975). An early investigation including a contemporary clinical whole-body SPECT system acquiring torso data posterior to a prone lying patient was shown to improve overall image quality by reducing both bias and variance between images (Metzler *et al* 2002), but this implementation is considered somewhat impractical for a dedicated, stand-alone breast SPECT system. Overall image quality (e.g. signal-to-noise ratios, contrast, bias and variance) was assessed in the development of such trajectories. While the sampling criteria are satisfied for much of the breast volume in a variety of developed trajectories (Archer *et al* 2003), incomplete sampling of the heart and liver causes streak artifacts throughout the reconstructed volume, hindering the ability to perceive (hence quantitate) potential lesions in the chest wall, axilla and even the breast. Therefore, in this work, we systematically investigate the nature of the contamination due to the physical locations of the heart and liver, in order to develop trajectories which minimize or completely avoid views of these organs and could result in superior lesion visibility, as well as quantification.

2. Materials and methods

2.1. Overview of the SPECT system

The data for this study were collected with the SPECT sub-system of our hybrid dual modality dedicated breast SPECT-CT system (Madhav *et al* 2009). Currently, the emission and transmission data are collected separately and sequentially (Cutler *et al* 2007). Therefore, the CT sub-system was not considered nor used for the acquisition of this data, and references detailing its components and characterization can be found elsewhere (McKinley 2006, Tornai *et al* 2005b). The SPECT sub-system is detailed in prior publications (Brzymialkiewicz *et al* 2005, Tornai *et al* 2003), but in brief, it comprise 2.3 mm CZT pixels spaced at 2.5 mm pitch in an array measuring 16×20 cm (LumaGEM 3200S, Gamma Medica, Northridge, CA). The camera has an attached high resolution (2.54 cm height), parallel-hole collimator and has a combined sensitivity of 37.9 cps/MBq. The energy resolution is 6.7% FWHM at 140 keV, and as indicated in an observer study, we can reliably visualize and resolve ~3 mm hot spots from reconstructed SPECT data (Cutler *et al* 2010).

The detector system is attached to a laboratory jack (model M-EL120, *Newport Corp.*, Irvine, CA) and goniometer (model BGM200PE, *Newport Corp.*, Irvine, CA) which provide the maneuverability for fully flexible, three-dimensional (3D) trajectories traversing a hemisphere, within which a pendant breast would be suspended. The hybrid SPECT-CT system is united on a common azimuthal rotation stage (model RV350CC, *Newport Corp.*, Irvine, CA), which rotates the subsystems about the breast's chest-to-nipple (central) axis. A crosshair laser (model 920-023273, *StockerYale*, Dollard-des-Ormeaux, Québec) which we integrated into the system assists in quickly aligning an object's center of mass along the center of rotation.

2.2. Anthropomorphic phantom

A large anthropomorphic left-breast phantom (*Radiological Support Devices Inc.*, Newport Beach, CA), with a thin-walled balloon lesion (*Harvard Apparatus*, Holliston, MA) near the chest wall and an acrylic-walled spherical lesion near the center of the breast, attached to a torso containing heart and liver phantoms was filled with clinically realistic concentration ratios (Maublant *et al* 1996) of aqueous ^{99m}Tc pertechnetate simulating biological radiotracer uptake (table 1). The heart phantom consists of two compartments—(1) the outer wall and (2) the inner atriums and ventricles—of which the activity was added only to the outer wall. The phantom was set up on our custom-designed patient bed (Crotty *et al* 2006, 2007) with the breast phantom's chest-to-nipple axis placed at the center of rotation of the hybrid system.

2.3. Data acquisition

Projection data acquired with tilted parallel beam (TPB) trajectories at fixed polar angles of 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50° and 60° were collected for 128 step-and-shoot projections over 360° azimuth (figure 1, left). The data were acquired with a $\pm 4\%$ energy window centered about the 140 keV photopeak from ^{99m}Tc . All scans started and finished at the same azimuthal position—the left lateral side of the left breast phantom (figure 1). The detector system had a predefined and varying radius of rotation that contoured the breast phantom's non-uniform shape. The phantom was not repositioned on the bed between scans. Each scan was acquired for 10 min (5 s per projection), and since the duration of an entire dataset collection (1.5 h) was much less than the half life of the radionuclide (6.06 h), the acquisition time was not adjusted for radioactive decay.

For each data acquisition set, the counts in each projection were integrated and plotted.

2.4. Image reconstruction and data analysis

Projection files were reconstructed via an iterative ordered subsets expectation maximization algorithm (OSEM) using a ray-driven image reconstruction code (Bowsher *et al* 1996). Reconstruction parameters included eight subsets and a support grid size of $160 \times 160 \times 160$ with a voxel size of 2.5 mm^3 . Attenuation correction was applied by assigning a uniform attenuation coefficient of 0.1545 cm^{-1} (μ value for water at 140 keV) to all voxels within the bounds of the uniform breast phantom from each reconstruction. To investigate the effect of cardiac and hepatic contamination, the mean count value and standard deviation for regions of interest (ROI) in coronal slices near the chest wall, center, and nipple of the breast phantom were measured and compared.

As previously determined, the second iteration of data is a good compromise to maximize both contrast and signal-to-noise ratio (SNR) for these types of emission breast data, and thus, was used for subsequent analysis (Brzymialkiewicz 2005). For each lesion, the SNR, contrast and full width at half maximum (FWHM) were calculated and compared for the coronal and transverse planes of each dataset. The SNR was calculated by summing three

planes in the center of the lesion and taking the difference in the mean lesion ROI value and the mean background ROI value and dividing by the standard deviation of the background ROI. The contrast was calculated using the same signal difference numerator and dividing it by the mean background ROI value in the three summed planes. The FWHM of the lesion was determined by obtaining a profile through the lesion and using the KaleidaGraph software (*Synergy Software*, Reading, PA) to fit a Gaussian function with a least-squares regression about the peak.

2.5. Applying results

The results obtained from analyzing where the counts acquired per projection deviated from the baseline counts in the breast (i.e. comparing with TPB15°) were utilized to determine the polar angles at which the gamma camera could acquire signals originating in the heart and liver. An acquisition trajectory commonly used in our lab, projected sinusoid (PROJSINE), was consequently modified to avoid the cardiac and hepatic signal by constraining its polar range. Over a 360° rotation, the standard PROJSINE path traverses three lobes ranging in polar tilt, usually from 15° to 45° (figure 2). This trajectory has been shown to improve sampling and yield distortion-free object shapes (Brzymialkiewicz *et al* 2006). The previously described phantom (section 2.2) was setup again, but the absolute lesion to breast radioactive concentrations slightly varied (6.6:1). It was sampled with TPB15° and TPB45° (for direct comparison), standard PROJSINE and, based on results, constrained PROJSINE trajectories. The two datasets were reconstructed and compared qualitatively and quantitatively using the methods in section 2.4.

3. Results

3.1. Qualitative image assessment

Reconstructed images are shown in figures 3 and 4. Figure 3 shows the sum of the three coronal slices of attenuation corrected data containing the chest wall lesion. The top and left in the coronal slices correspond to the superior and (left) lateral sides of the left breast phantom, respectively. Due to the visual similarity of the data in the coronal plane, the reconstructed slices containing the centered lesion are not shown. Figure 4 shows the sum of eight transverse slices (for display of both lesions simultaneously) containing both lesions. Those images comprise summed slices encompassing the lesions of attenuation corrected data. The left side of the transverse slices corresponds to the left, lateral side of the left breast phantom.

In the coronal reconstructed slices of the chest wall lesion (figure 3) from the 45°, 50° and 60° polar angle acquisitions, the edge in the inferior, medial quadrant (bottom, right) is blurred and not as well defined as the phantom edges in images acquired at shallower polar angles. Notable in the transverse images (figure 4) acquired with 40–60° polar angles is an elongation of the breast along with an elongation and overlap of the lesions, most clearly seen in the last image. This is consistent with previous studies on a clinical SPECT camera (Pieper *et al* 2001, 2002) as well as the classic insufficient sampling artifact seen by all incomplete angle tomography systems, namely those using ‘tomosynthesis’. Additionally in the transverse images, varying depths into the chest wall region are imaged with the activity originating from the heart and liver appearing at the upper edge of the images acquired with 35–60° polar angles.

3.2. Azimuthal count distribution

From each of the 128 projections acquired, the integrated counts were plotted as a function of the azimuthal position from which they were obtained (figure 5). The curves illustrate that as the polar angle increases, the number of counts per projection also increases. In this left-

breast experimental setup, the most dramatic increase is in the upper-right quadrant of the plot or at the angular position from which the camera has direct views of the heart and liver.

Other quadrants also show an increase in the total counts due to viewing an increasing breast volume, as well as a portion of the torso, i.e. including the chest wall and axilla. These additional counts are not considered problematic, but rather may be desirable because these regions are of clinical interest. Because normal torso tissue has been shown to uptake a similar amount of radiotracer to that of normal breast (Maublant *et al* 1996), it is unlikely that additional activity from these regions will cause streak artifacts; however, this low frequency background could degrade contrast and/or affect absolute activity quantification.

Therefore, a bound on the polar angles for each azimuthal position of this dataset is determined whereby the camera could maximize the volume of breast and chest wall imaged, while avoiding direct views of the heart and liver (figure 6). Many trajectories could be made within this boundary allowing adequately sampled left-breast and neighboring tissue. The left-breast boundary mirrored about the x -axis would likely be the boundary limiting the maximum polar angle to image the right breast, while avoiding direct views of the heart and liver.

3.3. Mean and standard deviation of counts in breast

Despite that attenuation correction has been applied to the data sets, the mean value of the uniform breast background is not equal throughout the breast volume for a given acquisition setup. Figure 7 displays the mean breast phantom background count value for coronal slices near the chest wall (though not containing the heart and liver), in the center (not containing the lesion) and near the nipple. All values were measured on approximately the same fully reconstructed slice in each image. The non-lesion containing ROIs encompassed the majority of the coronal slice of the breast. Within one standard deviation, the mean counts for each of the regions on each of the scans appear to be approximately equal. However, there was a statistically significant difference ($p < 0.01$) between a paired t -test of the mean values in the different regions.

3.4. SNR and contrast

There appears to be a bigger difference between SNRs and contrasts for the chest-wall and center breast lesions with increasing polar tilt angle, illustrated as the ratio of those figures of merit (figure 8). Ideally, the values would be near one another regardless of the location in the breast, bringing the ratio close to 1. There is a larger difference between the SNRs and contrasts of the chest wall lesion compared with the centered lesion. This larger difference may be due to incomplete resolution recovery of the lesion volumes and potentially background contamination from the cardiac and hepatic activity.

3.5. FWHM

The FWHM values associated with the line profiles are sensitive to where the profiles are drawn. The two pixel-wide line was drawn approximately through the center of the lesion. Though one caveat of determining the size of the lesion from the line profiles is that it is somewhat sensitive to the initial inputs, the overall coefficients of fit exceeded $R^2 = 0.95$. The FWHM of the lesions compared with the measured diameter of the lesions (~15 mm) indicates that for larger polar angles a narrowing and elongation occurs, distorting the shape of the lesion (figure 9). However, at shallow polar angles, this elongation does not appear to cause severe distortion artifacts.

3.6. Evaluation of the polar tilt boundary

The results from the sequential tilted trajectories indicate that data acquired within a limited polar range given that an azimuthal position will produce better qualitative and perhaps more easily quantifiable images. To determine any difference in image quality, two PROJSINE trajectories were additionally evaluated: (1) standard, three lobed PROJSINE with a polar range of 15–45° and (2) constrained, three lobed PROJSINE with one lobe's polar range from 15° to 30° and two lobes' polar range from 15° to 45° (figure 10). For the modified trajectory, a reduced number of counts were acquired in the upper-right quadrant compared to the normal PROJSINE trajectory (figure 10), indicating that indeed the direct views of the heart and liver had been eliminated from the acquisition.

As expected, the resulting reconstructed images appear with an area of enhanced activity in the chest wall for the image reconstructed from the data acquired outside the trajectory boundary, but not in the image reconstructed from the modified trajectory contained within the boundary (figure 11). Eight reconstructed, attenuation corrected slices containing both lesions are summed for display purposes. While artifacts due to the acquisition trajectory persist, the overall shape of the breast and lesions are preserved, corresponding to the known shapes and dimensions of those phantoms. The counts acquired per projection for the constrained PROJSINE closely followed those of the TPB15° acquisition; however when comparing the reconstructed images (figures 4 top left and 11 right), much more of the chest wall volume is included in the constrained PROJSINE data, along with the noticeable absence of contamination events from the heart and liver.

The ratios (center lesion:chest wall lesion) of the SNR and contrast for the normal and modified data acquisitions are given in table 2. The ratios of the SNR and contrast of the center to chest wall lesion for the re-acquired TPB15° data are in line with the general trend outlined in figure 8. Both the unmodified and constrained PROJSINE trajectories produce ratios closer to one than the TPB trajectories, most likely because they more completely sample the breast. The difference between the two lesions is slightly larger in the constrained trajectory, but the overall image has better quality with fewer streak artifacts or high noise pixels.

4. Discussion

Given the variations in photopeak counts acquired for projections at a variety of polar tilt angles, acquisition trajectories can be created to avoid or minimize background contamination, especially by constraining the trajectories within a boundary set of polar and azimuthal angles. One caveat is that there are natural variations in the locations of human subjects' hearts and livers, as well as their sizes (girth, height and weight) and organ sizes. Nonetheless, the boundary conditions demonstrated here provide a general guideline within which trajectories can be created and modified for individuals. For example, a few scout planar images prior to the scan could help determine gross variations in the bounding polar angles. This has to be further investigated with clinical studies.

The object shape distortions in the transverse (and also sagittal planes) are due primarily to the incomplete sampling associated with the angular tilts of the gamma camera (Pieper 2002). This is a major and well-known limitation in other tomosynthesis (limited angle) imaging approaches. Here, the trend in the mean count rates increasing from the chest wall to the nipple might indicate the difficulty in attenuation correction for these insufficiently sampled datasets. The quantitative FWHM measurements along with the clear visualization in the transverse (or sagittal) planes of the reconstructed images confirm that an elongation and narrowing of not only the overall breast shape, but also focal lesions occur for data acquired with large polar angles. Incomplete sampling is primarily to blame for these

distortions, and the issue is otherwise well known and has been characterized (Brzymialkiewicz 2005, Orlov 1975).

Figures of merit using SNR and contrast indicate an increasing difference in values of the two lesions as the polar tilt increases, further lending credence to the use of boundary values to limit the trajectories. The relative image quality appears to be influenced by both angular sampling and contamination from the heart and liver, and the minimization (near elimination) of secondary organ contamination clearly improves the imaging results. However, additional studies need to be done after scatter correction has been implemented for more quantitative imaging evaluation. The scatter contribution in emission imaging mainly causes an apparent increase in counts internal to an object, but attenuation yields a cupping artifact. It is not expected that incorporation of scatter correction would change the trends or overall conclusions, though better estimates of the absolute signal values would be more clear.

Although these experiments were acquired on a hybrid SPECT-CT system, a CT image was not acquired and used to correct for attenuation of the SPECT images. The very thin plastic (1 mm) phantoms used in these experiments were uniformly filled with water. Therefore, a mask of the reconstructed SPECT image filled with the attenuation coefficient of water is a very good representation of the volumetric attenuation map of the phantom. While it should be noted that a patient's breast is actually more heterogenous in tissue content and distribution, at 140 keV, the difference in attenuation coefficients for glandular and fatty tissues is very small, and a single uniform value for 'breast tissue' may be a satisfactory assumption for our purposes. Nevertheless, work is underway to implement a CT-based attenuation map due to other advantages that such a CT-based correction can have, such as anatomical registration and the ability for joint reconstruction. One caveat is that attenuation correction results using CT-based images might complicate these SPECT results since the shape of those attenuation images would not strictly match the distorted shapes of these reconstructed SPECT images, yielding over and under-compensated regions throughout the reconstructed-corrected volumes. This shape mismatch also needs further investigation.

We routinely use TPB 45° for imaging studies in our lab since it has provided high quality images for a majority of imaging tasks, such as when a hot or cold volume is located near the nipple region of a breast (Brzymialkiewicz *et al* 2006, Cutler 2007). However, given that a simple fixed-polar tilted orbit clearly is an undersampled dataset, other trajectories which more completely sample more of the breast including any potential (or occult) lesions should be utilized. Having identified boundary values for degrees of polar tilt using an anthropomorphic torso phantom in this dedicated breast imaging scheme, we recommend that trajectories be defined within such a boundary in an effort to achieve more qualitatively accurate and quantitative information. Streak artifacts and other signal degrading effects from the heart and liver activity can be minimized or avoided altogether. There will be tradeoffs between the volume of tissue being imaged and accuracy of the reconstruction, and therefore potential effects on absolute activity quantification.

5. Conclusions

Imaging an anthropomorphic phantom filled with clinically realistic concentration ratios of radioactivity using sequential tilted trajectories of increasing polar angle has facilitated determining the viewpoints at which the parallel-hole collimated detector has direct views of the heart and liver activity. We demonstrated that adequate chest wall coverage can be obtained with trajectories that also avoid direct heart and liver projection views. Further studies in human subjects are planned to validate this recommendation for clinical imaging. Future work also entails attempting to obtain quantitative images including all appropriate

corrections, especially for those lesions residing near the chest wall region where simple attenuation correction still appears to undercorrect the uniform background values.

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References

- Archer CN, Tornai MP, Bowsher JE. Implementation and initial characterization of acquisition orbits with a dedicated emission mammotomograph. *IEEE Trans. Nucl. Sci.* 2003; 50:413–20.
- Bowsher JE, Johnson VE, Turkington TG, Jaszczak RJ, Floyd CR, Coleman RE. Bayesian reconstruction and use of anatomical *a priori* information for emission tomography. *IEEE Trans. Med. imaging.* 1996; 15:673–86. [PubMed: 18215949]
- Brem RF, Floerke AC, Rapelyea JA, Teal C, Kelly T, Mathur V. Breast-specific gamma imaging as an adjunct imaging modality for the diagnosis of breast cancer. *Radiology.* 2008; 247:651–7. [PubMed: 18487533]
- Brem RF, Rapelyea JA, Zisman G, Mohtashemi K, Raub J, Teal CB, Majewski S, Welch BL. Occult breast cancer: scintimammography with high-resolution breast-specific gamma camera in women at high risk for breast cancer. *Radiology.* 2005; 237:274–80. [PubMed: 16126919]
- Brzymialkiewicz C, Tornai M, McKinley R, Bowsher J. Evaluation of fully 3D emission mammotomography with a compact cadmium zinc telluride detector. *IEEE Trans. Med. Imaging.* 2005; 24:10.
- Brzymialkiewicz, CN. PhD Thesis. Duke University; 2005. Development and evaluation of a dedicated emission mammotomography system.
- Brzymialkiewicz CN, Tornai MP, McKinley RL, Cutler SJ, Bowsher JE. Performance of dedicated emission mammotomography for various breast shapes and sizes. *Phys. Med. Biol.* 2006; 51:5051–64. [PubMed: 16985287]
- Crotty, DJ.; Madhav, P.; McKinley, RL.; Tornai, MP. Patient bed design for an integrated SPECT-CT dedicated mammotomography system. *IEEE Nuclear Science Symp. Conf. Record*; 2006. p. 3915-9.
- Crotty DJ, Madhav P, McKinley RL, Tornai MP. Investigating novel patient bed designs for use in a hybrid dual modality dedicated 3D breast imaging system. *Proc. SPIE.* 2007; 6510:65101H.
- Cutler, SJ. Biomedical Engineering. Duke University; Durham, NC: 2007. Pre-clinical evaluation of a dedicated SPECT-CT mammotomography system for quantitative hybrid breast imaging.
- Cutler, SJ.; Madhav, P.; Perez, KL.; Crotty, DJ.; Tornai, MP. Comparison of reduced angle and fully 3D acquisition sequencing and trajectories for dual-modality mammotomography. *IEEE Nuclear Science Symp. Conf. Record*, 2007 (NSS '07); 2007. p. 4044-50.
- Cutler SJ, Perez KL, Barnhart HX, Tornai MP. Observer detection limits for a dedicated SPECT breast imaging system. *Phys. Med. Biol.* 2010; 55:1903. [PubMed: 20224159]
- Hruska CB, O'Connor MK. A Monte Carlo model for energy spectra analysis in dedicated nuclear breast imaging. *IEEE Trans. Nucl. Sci.* 2008; 55:10.
- Hruska CB, O'Connor MK, Collins DA. Comparison of small field of view gamma camera systems for scintimammography. *Nucl. Med. Commun.* 2005; 26:441–5. [PubMed: 15838427]
- Hruska CB, Phillips SW, Whaley DH, Rhodes DJ, O'Connor MK. Molecular breast imaging: use of a dual-head dedicated gamma camera to detect small breast tumors. *Am. J. Roentgenol.* 2008; 191:1805–15. [PubMed: 19020253]
- Madhav P, Crotty DJ, McKinley RL, Tornai MP. Evaluation of tilted cone-beam CT orbits in the development of a dedicated hybrid mammotomograph. *Phys. Med. Biol.* 2009; 54:3659–76. [PubMed: 19478374]

- Maublant J, de Latour M, Mestas D, Clemenson A, Charrier S, Feillel V, Le Bouedec G, Kaufmann P, Dauplat J, Veyre A. Technetium-99 m-sestamibi uptake in breast tumor and associated lymph nodes. *J. Nucl. Med.* 1996; 37:922–5. [PubMed: 8683312]
- McKinley, R. Biomedical Engineering. Duke University; Durham, NC: 2006. Design and characterization of a dedicated computed mammotomography system.
- Metzler SD, Bowsher JE, Tornai MP, Pieper BC, Peter J, Jaszczak RJ. SPECT breast imaging combining horizontal and vertical axes of rotation. *IEEE Trans. Nucl. Sci.* 2002; 49:31–6.
- O'Connor MK, Phillips SW, Hruska CB, Rhodes DJ, Collins DA. Molecular breast imaging: advantages and limitations of a scintimammographic technique in patients with small breast tumors. *Breast J.* 2007; 13:3–11. [PubMed: 17214787]
- Orlov SS. Theory of three-dimensional reconstruction. *Sov. Phys. Crystallogr.* 1975; 20:312–4.
- Phelps ME. Emission computed tomography. *Semin. Nucl. Med.* 1977; 7:337–65. [PubMed: 918674]
- Pieper BC, Bowsher JE, Tornai MP, Archer CN, Jaszczak RJ. Parallel-beam tilted-head analytic SPECT reconstruction: derivation and comparison with OSEM. *IEEE Trans. Nucl. Sci.* 2002; 49:2394–400.
- Pieper BC, Bowsher JE, Tornai MP, Peter J, Greer KL, Jaszczak RJ. Breast tumor imaging using a tiltable head SPECT camera. *IEEE Trans. Nucl. Sci.* 2001; 48:1477–82.
- Santoro GM, Bisi G, Sciagra R, Antonucci D, De Cristofaro MT, Dovellini EV, Pupi A, Zeraushek M, Fazzini PF. Study of myocardial perfusion at rest using technetium Tc 99m methoxy-isobutylisonitrile: comparison with labeled microspheres and thallium 201. *G. Ital. Cardiol.* 1988; 18:907–13. [PubMed: 3266855]
- Savi A, Gerundini P, Zoli P, Maffioli L, Compierchio A, Colombo F, Matarrese M, Deutsch E. Biodistribution of Tc-99m methoxy-isobutyl-isonitrile (MIBI) in humans. *Eur. J. Nucl. Med.* 1989; 15:597–600. [PubMed: 2598955]
- Scopinaro F, Schillaci O, Scarpini M, Mingazzini PL, Di Macio L, Banci M, Danieli R, Zerilli M, Limiti MR, Colella A Centi. Technetium-99m sestamibi: an indicator of breast cancer invasiveness. *Eur. J. Nucl. Med.* 1994; 21:984–7. [PubMed: 7527779]
- Spanu A, Cottu P, Manca A, Chessa F, Sanna D, Madeddu G. Scintimammography with dedicated breast camera in unifocal and multifocal/multicentric primary breast cancer detection: a comparative study with SPECT. *Int. J. Oncol.* 2007; 31:369–77. [PubMed: 17611694]
- Taillefer R, Dupras G, Sporn V, Rigo P, Leveille J, Boucher P, Perez-Balino N, Camin LL, McKusick KA. Myocardial perfusion imaging with a new radiotracer, technetium-99 m-hexamibi (methoxy isobutyl isonitrile): comparison with thallium-201 imaging. *Clin. Nucl. Med.* 1989; 14:89–96. [PubMed: 2731400]
- Tofani A, Sciuto R, Semprebene A, Festa A, Pasqualoni R, Giunta S, Mottolise M, Benevolo M, Botti C, Maini CL. 99Tcm-MIBI scintimammography in 300 consecutive patients: factors that may affect accuracy. *Nucl. Med. Commun.* 1999; 20:1113–21. [PubMed: 10664992]
- Tornai M, Bowsher J, Archer C, Peter J, Jaszczak R, MacDonald L, Pratt B, Iwanczyk J. A 3D gantry single photon emission tomography with hemispherical coverage for dedicated breast imaging. *Nucl. Inst. Methods Phys. Res. A.* 2003; 497:157–67.
- Tornai M, Bryzmialkiewicz C, Bradshaw M, Bowsher J, Pratt B, Iwanczyk J, Li J, MacDonald L. Comparison of compact gamma cameras with 1.3 mm and 2.0 mm quantized elements for dedicated emission mammotomography. *IEEE Trans. Nucl. Sci.* 2005a; 52:6.
- Tornai M, McKinley R, Bryzmialkiewicz C, Madhav P, Cutler S, Crotty D, Bowsher J, Samei E, Floyd C. Design and development of a fully 3D dedicated x-ray computed mammotomography system. *Proc. SPIE.* 2005b; 5745:189.
- Wang H, Scarfone C, Greer K, Coleman R, Jaszczak R. Prone breast tumor imaging using vertical axis-of-rotation (VAOR) SPECT systems: an initial study. *IEEE Trans. Nucl. Sci.* 1997; 44:6.
- Williams, MB.; Narayanan, D.; More, MJ.; Goodale, PJ.; Majewski, S.; Kieper, D. Analysis of position dependent compton scattering in scintimammography with mild compression. *IEEE Nuclear Science Symp. Record* 2002; 2003. p. 863-7.

Figure 1.

(left) Three-dimensional rendition of the TPB trajectories with polar angles ranging from 15° to 60° . The radius of rotation was varied such that the gamma camera was in closest proximity to the breast phantom for each trajectory. For clarity, the drawing is spaced to more clearly illustrate each trajectory. Middle: schematic, scaled, top-down drawing of the SPECT system overlaid with polar coordinates and approximate relative positioning of the heart (light gray, heart shape) and liver (dark gray, oval shape). A horizontal arrow points along a patient long axis toward the head. The SPECT camera is at the top, 90° position. From this initial position, the detector system rotates clockwise 360° . Right: photograph of the experimental setup shown at the starting camera position and orientation of the phantoms.

Figure 2.

Left: three-dimensional rendition of the trajectory (dotted lines) of the SPECT camera around the breast for the standard PROJSINE trajectory ranging in polar tilt from 15° to 45° . The center of the camera's FOV follows along the dotted path. Right: two-dimensional polar plot of PROJSINE trajectory.

Figure 3.

Images of three summed, coronal slices of OSEM reconstructed, attenuation corrected breast phantom data that include the 1.6 mL chest wall lesion, acquired at the indicated polar angles (shown in the lower-right corner). Note in the lower-right corner of the TPB60° image that the edge of the breast is distorted, and that the apparent lesion size decreases with increasing angular tilt. This is seen as elongation in the transverse views (figure 4).

Figure 4.

Images of eight summed transverse slices of OSEM reconstructed, attenuation corrected breast phantom data containing both lesions, acquired at the indicated polar angles. Note the elongation and distortion of the breast phantom and contained lesions with increasing polar angle. At polar angles $\geq 35^\circ$, cardiac and hepatic activity is seen at the chest wall of the images (black arrow in 60° data).

Figure 5.

Normalized counts acquired per projection for each dataset. These smoothed data are depicted in alternating black and gray, with the inner black line representing 15° polar tilt and the outermost black line representing 60° tilt. The number of counts acquired increases with increasing tilt angle due to a greater volume of the phantom being imaged as well as direct views of the torso, heart and liver backgrounds.

Figure 6. The black line delineates the maximum polar angle for a trajectory which could contour the left breast while avoiding direct views of the heart and liver. The gray trajectory is the reflection of the maximum polar angle that could be used for the right breast.

Figure 7.

Means of a region of interest as a function of polar angle that encompasses the whole breast phantom image in the coronal slice near the chest wall (◆), center (■) and nipple (▲) of the breast. Note that the mean count values are statistically significantly lower at the chest wall than at the nipple.

Figure 8.

The ratio of the (left) SNR and (right) contrast of the centered lesion to the chest wall lesion in the coronal plane plotted as a function of the polar tilt shows that as the polar tilt increases, the difference between the SNR and contrast of these lesions increases.

Figure 9.

Measured FWHM as a function of the polar tilt for the chest wall and centered lesion phantoms obtained in the (left) coronal and (right) transverse planes. The thin-walled chest wall balloon lesion measured 15 mm in diameter (coronal view) and 20 mm in length (transverse view). The measured outer diameter of the centered acrylic lesion phantom is 17 mm and, with an acrylic wall thickness ~1 mm, the inner diameter is ~15 mm.

Figure 10.

(left) Polar plot of the normal (solid gray line) and modified (solid black line) PROJSINE acquisition trajectories overlaid with the experimentally determined maximum polar tilt per azimuthal angle (dashed light gray line). Middle: the constrained PROJSINE trajectory, in which one lobe (black arrow) ranges from 15° to 30° rather than 15° to 45° . Right: the dark gray and black lines indicate the counts per projection for the normal and modified PROJSINE trajectories, respectively. For a direct count comparison, the innermost and outermost light gray lines indicate the counts per projection for TPB 15° and TPB 45° acquired data.

Figure 11.

Images of eight summed reconstructed, attenuation corrected transverse slices of (left) unmodified and (right) constrained PROJSINE acquired data. In the chest wall region of the unmodified PROJSINE image, an enhanced region in the upper-right regions is apparent due to the heart and liver activity, consistent with earlier results.

Table 1

^{99m}Tc radioactivity distribution in phantom.

Organ	Volume (mL)	Absolute activity (mCi)	Radioactivity ratio relative to breast
Torso	7000	6.2	1
Heart	290	3.8	12
Liver	1010	11.9	12
Breast	1740	1.8	1
Chest wall lesion	1.6	0.011	6
Centered lesion	2.3	0.016	6

Table 2

Ratios of $\text{SNR}_{\text{center/chest}}$ and $\text{contrast}_{\text{center/chest}}$ for TPB and PROJSINE trajectories.

Trajectory	$\text{SNR}_{\text{center/chest}}$	$\text{Contrast}_{\text{center/chest}}$
TPB15	2.2	2.4
Unmodified PROJSINE	1.1	1.2
Constrained PROJSINE	1.4	1.4