#### MODIFICATION OF CT QUALITY ASSURANCE PHANTOM FOR PET/CT ALIGNMENT AND PET RESOLUTION

A Thesis

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### ABSTRACT

Radiotherapy treatment planning utilizing PET and CT is rapidly gaining acceptance in oncology. A limiting factor of the dual modality is the PET/CT alignment. A small error in PET/CT alignment may result in giving large doses of radiation to healthy tissues as a result of poor treatment planning. For this purpose, regular quality assurance testing of PET/CT must be performed. Separate QA procedures and phantoms have been developed for the two different modalities. In particular, many existing phantoms cannot be used for both modalities, which is a requirement for evaluating PET/CT alignment. Our goal is to evaluate several existing phantom designs to evaluate their utility for checking PET/CT alignment. The three phantoms investigated are a Gammex 464 phantom, a Triple-Line Source PET phantom, and a Hot Sphere PET phantom. The PET phantoms are unmodified the Gammex 464 phantom is modified to perform PET/CT alignment. The Gammex 464 phantom is typically used for routine quality assurance of CT scanners. Several CT parameters are determined with this phantom before and after modification. Then PET/CT alignment testing is performed using this modified CT phantom and the two other phantoms. Three methods have been used for analyzing the PET/CT images to measure the PET/CT alignment errors. The methods are the Manual method which calculates the alignment error from hand-drawn profiles, the Maximum-Pixel Value method which measures the error based on the pixel value of the objects in the PET/CT images, and the Curve-fitting method, which measures the alignment error by getting the best fit values for the object profiles. The Curve-fitting method also estimates the PET resolution from apparent size of objects in the phantoms.

Our PET/CT alignment data and results suggest that the Maximum-Pixel Value method for the modified phantom with acrylic insert is a good choice for measuring the PET/CT alignment error, providing a reasonable balance between computational analysis effort and measurement precision.

### **CHAPTER 1**

# **INTRODUCTION**

Accurate, patient-specific anatomical information is a prerequisite for successful radiation therapy planning and delivery to the entire extent of tumor, while minimizing dose to normal tissues surrounding it. For this reason, imaging in radiation oncology is very important. Many advances in radiation oncology have resulted from improvements in imaging modalities like computed tomography (CT), magnetic resonance imaging (MRI) and positron emission tomography (PET).<sup>1</sup> CT is a morphologically oriented imaging method. Unlike CT, PET is a functionally oriented method. PET with an FDG tracer utilizes the mechanism of biochemical reactions inside the patient and uses coincidence detection of annihilation photons to determine the tumor position. Both the methods have advantages as well as limitati

Historically, separate QA procedures and phantoms have been developed for the two different modalities. In particular, many existing phantoms cannot be used for both modalities, and for evaluating PET/CT alignment, a single QA phantom for both the modalities is a requirement. Our goal is to evaluate several existing phantom designs to evaluate their utility for checking PET/CT alignment. Ideally, the phantom should also allow other PET or CT QA measurements to be performed. If an existing phantom is modified to allow alignment testing, the effect of this modification should be insignificant on its routine QA. The final product of this thesis is a recommendation of a phantom and analysis method for PET/CT alignment QA.

## **1.1 Objectives**

The main objectives of this research can be summarized as follows

- Evaluate several QA phantoms for PET/CT alignment
- Evaluate different methods for measuring PET/CT alignment

The three phantoms investigated are a Gammex 464 ACR CT accreditation phantom, a Triple-Line Source PET phantom, and a Hot Sphere PET phantom. A detailed explanation with figures for these phantoms is provided in Chapter 3. The PET phantoms are unmodified, but the Gammex 464 is modified to perform PET/CT alignment. The Gammex 464 phantom is typically used for routine quality assurance of CT scanners. This phantom is modified in such a way that it can be used for PET/CT alignment parallel to performing routine CT QA. For all three phantoms, the PET and CT images are analyzed using three different methods for locating the centers of objects. Alignment error is determined, and the results are compared among the three phantoms. Also, regular CT QA is performed using the modified Gammex phantom and compared with

that of the original phantom to check the impact of the modification on its performance. Finally the estimated spatial resolution for the PET scanner is reported, because this is a typical PET QC parameter and it is calculated automatically as part of the PET/CT alignment analysis.

The modification to the Gammex phantom involves creating a hole in the phantom in which a radioactive insert is placed. Two different insert materials are compared for this purpose, with <sup>18</sup>F used as the radioactive source in both cases. Results show that modification of the phantom **odJ0eg01**aTCT0.0094peFfvorm0t00094alT-arB to 4[2shocl(0r8)29(2enTvanta)

description of materials used in this research is presented. In Chapter 4, the methods developed and used for this research are explained. In Chapter 5, results and discussions are provided while the conclusions of this research are given in Chapter 6.

# **CHAPTER 2**

# **BACKGROUND PHYSICS**

# 2.1 Computed Tomography (CT)

CT number (HU) = 
$$\frac{1000^* (\mu_i - \mu_w)}{\mu_w}$$
 (Equation 1)

The CT numbers are mapped to a grey scale or color display for visual interpretation. Because the human eye cannot distinguish among 2000 different shades of grey, only a limited range of CT numbers is displayed to allow the observer to interpret the image. Window level (WL) indicates typically the central HU of all the numbers while window width (WW) represents the range of HU being displayed.

Several types of modern CT designs are illustrated in Figure 1. Development of slip ring technology for CT scanners during the 1980's enabled the x-ray tube to rotate continuously in one direction around the patient. This led to the development of helical CT. Single ring and multi-detector CT systems are illustrated in Figure 1(a) and Figure 1(c) respectively. Figure 1(b) illustrates a single slice helical system while Figure 1(d) illustrates a multi-slice helical system. In helical CT, the patient table mechanically moves through the x-ray beam while the x-ray tube rotates continuously in one direction. With this technology, information is acquired rapidly as a continuous volume of slices which allows larger anatomical regions of the body to be imaged in a single breath hold. This reduces the possibility of artifacts caused by patient movement and this also reduces scanning time. Contrast media often are used to improve contrast between the tissues of the body. These contrast media mostly contain high atomic mass substances and hence increase the attenuation coefficient of the organ.<sup>2</sup>



Figure 1: Different types of CT scanner systems: (a) one ring system, (b) single slice, helical system, (c) multi detector system, (d) multi slice helical.

### 2.2 Positron Emission Tomography (PET)

Positron emission tomography (PET) scanner design and performance have improved dramatically during the last decade. The first PET scanners were developed in the 1970's, though the first positron imaging started in the 1950's. The commercial production of PET scanners started in the mid 1980's. These scanners were limited to small volumes, but improvements have continued with better resolution and larger fields of view. By the mid-1990's, PET had become an important diagnostic tool.<sup>3</sup>

PET makes use of the physical characteristics of radioisotopes that decay by positron emission. PET is based on the principle of annihilation coincidence detection (ACD) of two anti-collinear 511 keV photons which are products of annihilation of a positron and an electron. PET imaging is functional imaging. It is a method to measure metabolic processes, such as oxygen utilization and glucose metabolism.<sup>4</sup>

Figure 2 illustrates the basic principle of annihilation coincidence detection. An event is counted if two 511 keV photons generated from positron-electron annihilation are detected by the two detectors within a small timing interval, .<sup>5</sup> Also, for the event to be regarded as valid, the subsequent line-of-response (LOR) formed between the detectors must be within the valid acceptance angle of the tomograph and the energy deposited in the detectors by both photons should be within a selected energy window.



Figure 2: Principle of annihilation coincidence detection of 511 keV photons.

Detection events can be classified into five types (Figure 3). Single events are when a single photon is detected by one detector. A true coincidence event (Figure 3c) occurs when two photons from a single positron-electron annihilation are detected within the timing window. A random event (Figure 3b) occurs when two photons not arising from the same annihilation event are incident on the detectors within the coincidence time window of the system. Multiple events are similar to random events, and occur when three events from two annihilations are detected within the timing window. A scattered event (Figure 3a) occurs when at least one of the detected photons has undergone at least one Compton scattering event prior to detection.



Figure 3: Illustrations of (a) scattered coincidence event, (b) random or multiple coincidence event and (c) true coincidence event. Each detected gamma ray is a single event.

### **2.3 PET/CT Dual Modality**

One of the earliest dual-modality devices consisted of a scanner with combined

anatomical (CT) and functional (single photon emission computed tomography [SPECT])

capabilities.

obtained from the CT images were also used to generate attenuation maps for correction of the SPECT data. The device allowed simultaneous emission-transmission acquisitions. This concept of a single device capable of performing both functional and anatomical imaging led to the development of novel hybrid imaging systems with a significant improvement in the accuracy of attenuation correction and co-registration. These systems allow for sequential acquisition of anatomic and functional data by combined transmission (using CT) and emission (using either PET, SPECT, or gamma camerabased coincidence detection) acquisitions during a single session.<sup>8</sup> SPECT/CT offers some advantages for imaging of small animals although PET/CT has generally been favored for clinical applications.<sup>9</sup>

Dual PET/CT scanners, along with the rapid growth of the clinical use of PET imaging have acquired an important role in oncologic imaging.<sup>10-12</sup> The combination of PET and CT scanning offers unique opportunities for oncology. PET/CT has the ability to provide a synergistic combination of PET and CT images, which could potentially be more valuable than the two exams performed separately.

information obtained from functional studies in nuclear medicine. Registration of images can be performed using one of several methods. These include interactive registration, landmark-based registration, surface matching, maximization of mutual information, and elastic registration.

Fusion methods for separate functional and structural imaging data are usually based on extrinsic or intrinsic body markers.<sup>8</sup> External fiducial markers are attached to the body surface. These provide the required transformation if the markers are positioned identically for both studies. External markers are unsatisfactory for routine use because of the need for complex patient preparation and prospective planning; often, the studies are performed on different days, in different geographic locations, and using different types of imaging tables. Measurements based on surface points may not extrapolate well to points in the interior of the body. Internal anatomical landmarks eliminate the need for external fiducial markers and patient preparation. Reliable identification and accurate localization of these landmarks is, however, not always possible and requires considerable operator skill. These drawbacks are more prominent in nuclear medicine studies, which suffer from relatively low resolution.<sup>16</sup>

Inaccurate registration of separately acquired data may be due to differences in patient positioning between studies, as well as to differences in internal organ location, position, filling status, and volume at the time of imaging. Phantom validation to demonstrate methods for assessing the accuracy of PET/CT alignment has been studied by Lavely, et al.<sup>17</sup> They have used the IAEA (International Atomic Energy Agency) brain phantom and an anthropomorphic head phantom for assessment of PET/CT image registration. In this study, comparison of structure-based registration with fiducial based

registration was performed and a target registration error was computed at each point in a three dimensional grid that spans the image volume.

Sequential acquisition of PET and CT data during a single imaging session can potentially eliminate many of the errors described with co-registration of independent studies and excludes the need for internal or external fiducial markers and complicated mathematical registration algorithms.<sup>12,18</sup> Alignment in dual PET/CT scanners is achieved with mechanical alignment of the PET and CT gantries, and also by using a common imaging table for both systems. A number of factors must be controlled to define reliable tumor treatment volume data in radiation oncology.<sup>19</sup> These factors are registration error, lack of uniformity of PET resolution over the field of view (FOV), and attenuation and scatter corrections applied to the PET data.

### **CHAPTER 3**

### MATERIALS

This chapter describes the phantoms used in this work. These phantoms are commercially available, but include some modifications. The applications of these phantoms, the specifications given by manufacturers, and the limitations of these phantoms are explained in this chapter. The three phantoms investigated are a Gammex 464 ACR CT accreditation phantom, a Triple-Line Source PET phantom, and a Hot Sphere PET phantom. The CT QA phantom, Gammex 464 is chosen for modification as it can be used for routine QA measuring many CT parameters other than the PET/CT alignment and PET resolution for which it is modified. Other phantoms are not selected for the modification as they can be used for testing of fewer QA parameters.

#### **3.1 ACR CT Accreditation Phantom, Gammex 464**

The ACR CT Accreditation phantom is used for initial CT quality assurance assessment and routine monthly CT QA testing; routine QA helps in providing required image quality. It is made of solid water, making this phantom a physically stable device that provides reproducible results over time.<sup>20</sup> This phantom is designed for evaluating CT parameters such as positioning accuracy, CT number accuracy, slice width, low contrast resolution, high contrast resolution, CT number uniformity and image noise. Table 1 details the specifications of this phantom.

Table 1: Specifications for Gammex 464 phantom

Parameter	Value
Number of modules	4
Depth of each module	4 cm
Diameter of each module	20 cm
Modulematerial	Solid water
Module 1	CT number accuracy, slice thickness measurement
Module 2	Low contrast resolution measurement
Module 3	Uniformity measurement
Module 4	High contrast resolution measurement

# 3.2 Modified ACR CT Accreditation Phantom, Gammex 464

The ACR CT Accreditation phantom was modified by making four cylindrical holes parallel to the cylinder axis. Two holes are visible in Figure 5. Two holes are in each end of the phantom. Each CR Ci Tc 0.19951mt



Figure 6: (a) Triple-line phantom and (b) Triple-line phantom mounted inside the ECT cylinder.

Table 2: Specifications for Triple-line Insert for Deluxe SPECT phantom

Parameter	Value
Diameter of insert	18.6 cm
Diameter of line sources	~ 1 mm
Center to center spacing of line sources	7.5 cm
Useful height of line sources	7 cm
Location of the line sources	Center, 12 o' clock, 3 o' clock
Phantom material	acrylic

#### 3.5 Hot Sphere Phantom

The Hot Sphere phantom comprises a set of hollow spheres (Figure 7) in the same outer water-filled cylinder used for the Triple-line Source phantoms. Similar to the Triple-line Source phantom, the Hot Sphere phantom is recommended to evaluate PET image quality and to assess PET/CT alignment.<sup>22</sup> This phantom is used for evaluation of spatial resolution, attenuation and scatter effects, evaluation of reconstruction methods, and research. Specifications for the spheres are given in Table 3.



Figure 7: Hot Sphere phantom comprising hollow sphere set.

## **CHAPTER 4**

## **METHODS**

# 4.1 CT Quality Assurance

The Gammex 464 ACR Accreditation phantom is a CT phantom designed to perform routine QA testing of CT scanners. It is made of four modules and each module is designed to check a set of CT parameters. The parameters that were studied in this project are CT number calibration, slice thickness, low contrast resolution, high contrast resolution and uniformity. All tests were performed following the instructions given in the Instruction Manual<sup>20</sup> for the ACR CT Accreditation Phantom.

In the CT scanner workstation, we created a protocol to execute the necessary image acquisitions for the different QA tests. Once the phantom is aligned with the laser lights of the scanner, the protocol is run to acquire the QA images. After the images are acquired, analysis to evaluate CT parameters is done following the procedure in the Instruction Manual.

### **4.2 PET/CT Alignment Testing**

PET/CT alignment testing is performe

the PET/CT scanner and a CT scan is followed by a 4-minute 2D PET acquisition and a 3-minute 3D PET acquisition. The PET computer produces four different sets of reconstructed images for these scans. These are PET 2D acquisition with iterative reconstruction and measured attenuation correction (PET 2D IRMAC), PET 2D acquisition using iterative reconstruction without attenuation correction (PET 3D No AC), PET 3D acquisition with iterative reconstruction using iterative reconstruction and PET 3D acquisition using iterative reconstruction with iterative reconstruction and measured attenuation correction (PET 3D IRMAC), and PET 3D acquisition using iterative reconstruction without measured attenuation correction (PET 3D IRMAC), and PET 3D Acquisition using iterative reconstruction without measured attenuation correction (PET 3D No AC).

#### 4.2.2 PET/CT Image Analysis

The PET/CT images obtained are analyzed using software IDL 5.6 Student Edition. Image analysis is performed using a manual method, a maximum-pixel value method and a curve-fitting method to measure the center co-ordinates of the objects in the images. In all three methods, the center co-ordinates of the objects in the CT images are compared with those of the PET images. The methods differ in the manner by which the center coordinates are extracted from the images. In the Manual method, the center coordinates are extracted by drawing profiles across the object. The Maximum-Pixel Value method uses a computer code written in IDL to determine the center coordinates of the markers based on their pixel values. The Curve-fitting method uses IDL's curvefitting codes to extract the center coordinates of the markers.

#### 4.2.2.1 Manual Method

This method manually determines the center co-ordinates of the objects in the PET and CT images. In this method, a CT or PET image is displayed and the user draws a profile across the approximate diameter of the object using an in-built profiling tool,

PROFILE, in IDL. The co-ordinates of the peak (for PET) or center (for CT) of the profile provide the center co-ordinate of the object.

The Manual method applied to PET images obtained from the Triple Line Source phantom is illustrated in Figure 8 through Figure 10. The image to be analyzed is displayed using the READ DICOM subroutine in IDL (Figure 8). To compare the center coordinates of the objects, both the PET and the CT images must have the same pixel size. The PET images are resized, or rebinned, using the CONGRID subroutine in IDL to produce the PET images of same pixel sizes as of the CT images. The PET images obtained after rebinning have more pixels because the FOV of the PET scanner is larger than that of the CT scanner. These excess pixels are cropped uniformly from all edges of the PET matrix to get the PET images to the same number of pixels as the CT images. Figure 9 shows a resized PET image from the Triple Line Source phantom with all three sources visible. Points are selected on either side of the object, across which the profile is desired (Figure 9). The PROFILE subroutine in IDL plots the profile between the selected points. The coordinates for the peak of the profile curve are determined, which gives the center coordinates of the selected object (Figure 10). The center coordinates of the source, which are given in pixel numbers, are converted to position in millimeters by multiplying by the pixel size.

To find the coordinates for the CT image, the same process is followed except that the CT image doesn't require rebinning and cropping. Also, the CT profiles are rectangle functions rather than Gaussian functions as in the PET profiles. The Manual method applied to CT images of the Triple Line Source phantom is illustrated in Figure 11 through Figure 13. To obtain the center coordinates of the object for the CT image, the

coordinates of the center of the rectangle profile (Figure 13) are added to the starting







Figure 11: Screenshot showing a CT slice of the Triple-line Source phantom.


Figure 12: Screenshot showing the line for drawing a profile across the object on the CT image.



Figure 13: Screenshot displaying the profile of the selected object on the CT image.

# 4.2.2.2 Maximum-Pixel Value Method

For this method, a custom IDL procedure calculates the center co-ordinate of the

checks for the maximum pixel value from the other end, Q. The maximum value from the other end is found at B and the computer program stores the coordinates of B. Then the average of the coordinates A and B is calculated which is the required center coordinate of the object of interest.



Figure 14: Illustration of the Maximum-Pixel Value method using (a) PET image of a Triple-line Source phantom and (b) the profile of the object in the PET image of the Triple-line Source phantom.



Figure 15: Illustration of the Maximum-Pixel Value method using (a) CT image of a Triple-line Source phantom and (b) the profile of the object in the CT image of the Triple-line Source phantom.

a minimum. The center coordinates of the region at that particular location is taken as the desired center coordinate of the object of the phantom.

## **4.3 Determination of PET Resolution**

The Curve-fitting Method also estimates the spatial resolution of the PET scanner. Spatial resolution is determined from the fitted standard deviation of the Gaussian function. From the standard deviation () of the curve, the object size expressed as the full width at half maximum (FWHM) is given by Equation 2.

$$FWHM = 2.3548^{*}() \qquad (Equation 2)$$

The estimated spatial resolution is then given by Equation 3 where  $S_0$  is the known object diameter.

Resolution = 
$$\sqrt{(FWHM)^2 - (S_o)^2}$$
 (Equation 3)

For this thesis, resolution is estimated for all the different phantoms using the Curvefitting method and is checked for correlations with the measured alignment error results. One must note that this is only a rough approximation to the true spatial resolution. It is adequate for checking consistency between the PET images of the objects of different sizes, but cannot be interpreted as an accurate measurement of the spatial resolution of the PET scanner.

Table 4: CT acquisition and display parameters to perform CT number calibration as given in the instruction manual using the Gammex phantom

CT Acquisition Parameter	Value
kVp Setting	120 kV
mA Setting	55 mA
Technique	Adult Abdomen Technique
Slice Thickness	3.75 mm
Window Width (WW)	400
Window Level (WL)	0
Location	S0*

\* The alignment lasers are aligned on the center of module 1 of the phantom. This position is marked as S0 and all other image slices are referenced as millimeters superior (S) or inferior (I) to this mark



Figure 16: CT image of the modified Gammex phantom with acrylic insert displaying different materials of different densities used for CT number calibration.

Table 5: Acceptable CT number ranges for the Gammex phantom, specified by the ACR<sup>20</sup>

Motorial	Minimum CT Number	Maximum CT Number	
Waterial	(HU)	(HU)	
Polyethylene	-107	-87	
Bone	850	970	
Acrylic	110	130	
Air	-1005	-970	



Figure 17: CT number calibration for the different materials of the unmodified Gammex phantom and the modified Gammex phantom with either solid water or acrylic insert. The materials are (a) polyethylene, (b) bone, (c) acrylic, (d) air and (e) water.

## **5.1.2 Slice Thickness**

## 5.1.2.1 Determination of Slice Thickness at 120 kVp

CT acquisition parameters for determination of slice thickness were set according to instructions in the ACR Accreditation Manual, as summarized in Table 6. Figure 18 displays the slice thickness wires used for measurement of slice thickness. Shown in Figure 19, the slice thickness measured with the modified Gammex phantom with solid water or acrylic inserts equals the slice thickness specified in the acquisition set up. The slice thickness measured with the unmodified Gammex phantom is marginally different from the acquisition specification. Given the semi-quantitative method used, we conclude that all three phantoms are showing essentially the same behavior.

### 5.1.2.2 Verification of CT Number vs. kVp

The acquisition parameters are the same as those noted in Table 6 for the determination of slice thickness except that slice thickness is fixed at 3.75 mm and measurements are made at 80 kV, 100 kV, 120 kV, and 140 kV. The measured CT numbers were similar irrespective of the phantom used. While the CT number of water increases slightly with increase in kV, it is within the CT number ranges given in the Gammex manual (Figure 20).

### **5.1.3 Low Contrast Resolution**

CT acquisition parameters for determination of low contrast resolution were set according to instructions in the ACR Accreditation Manual, as summarized in Table 7. Low contrast resolution is measured using two different techniques, Routine Head technique and Adult Abdomen technique. The CT number of solid water on the largest low-contrast object as well as on the next object is found (Figure 21). Also the diameter of the smallest cylinder that is clearly visible is noted. The measured values using Routine Head technique are presented in Table 8 and using Adult Abdomen technique in Table 9. It can be observed that the measured values are consistent and within the range given in the Gammex manual.



- Figure 18: CT image of the modified Gammex phantom with acrylic insert showing the 0.5 mm wires used in determination of slice thickness.
- Table 6: CT acquisition and display parameters to determine slice thickness using Gammex phantom

CT Acquisition Parameter	Value
kVp	120 kV
mA	40-50 mA
Technique	Adult Abdomen Technique
Slice Thickness	2.5 mm, 5 mm, 7.5 mm
Window Width (WW)	400
Window Level (WL)	0
Location	SO*

<sup>\*</sup>Relative to the center of Module 1.





- Figure 20: CT number of water measured for a constant slice thickness as a function of kVp setting for (a) 80 kVp, (b) 100 kVp, (c) 120 kVp, and (d) 140 kVp.
- Table 7: CT acquisition and display parameters to determine low contrast resolution using Gammex phantom

CT Acquisition parameter	Value
--------------------------	-------



(a)

(b)

- Figure 21: CT image at S40 location illustrating determination of low contrast resolution (a) without region of interests (ROI) shown and (b) with ROIs shown.
- Table 8: Low contrast resolution performed using Routine Head technique with the Gammex phantoms

Phantom	Phantom Diameters of visible cylinders (mm)		CT number (next largest cylinder) (HU)
Gammex 464 6		94.6	89.37

## **5.1.4 High Contrast Resolution**

CT acquisition parameters for measurement of high contrast resolution are summarized in Table 10. High contrast resolution, or highest spatial frequency, is determined with both Adult Abdomen technique and High Resolution Chest technique. Both techniques are performed at 120 kV. Table 11 shows that the measured highest spatial frequency is the same for all three phantoms used. Figure 22 displays CT images of the modified Gammex phantom with acrylic insert, showing the high resolution bars used for measuring the highest spatial frequency.

## **5.1.5 Uniformity**

Table 12 gives the CT acquisition and display parameters for the determination of uniformity. CT number is measured at the 3,







Figure 23: (a) Uniformity measured with the modified and unmodified Gammex phantom, and (b) CT image of the modified Gammex phantom with acrylic insert at location S80 illustrating placement of center and edge regions of

CT PET 2D AC PET 2D No AC PET 3D AC PET 3D No AC



Figure 24: Measured center coordinates using the Manual method for the modified Gammex phantom with acrylic insert.

Table 13: Measured PET/CT alignment errors for the modified Gammex phantom





Figure 26: Measured center coordinates using the Manual

# 5.2.1.4 Triple-line Source





#### CT PET 2D AC PET 2D No AC PET 3D AC PET 3D No AC





CT DPET 2D AC PET 2D No AC PET 3D AC PET 3D No AC

# 5.2.2.2 Modified Gammex Phantom with Solid Water Insert

Figure 30 presents the measured center co



- Figure 30: Measured center coordinates using the Maximum-Pixel Value method for the modified Gammex phantom with solid water insert.
- Table 19: Measured PET/CT alignment errors for the modified Gammex phantom with solid water insert using the Maximum-pixel value method

Alignment error	2	2D	3D	
(mm) Attenuation Correction		No Attenuation Correction	Attenuation Correction	No Attenuation Correction
X <u>+</u>	0.58 <u>+</u> 0.76	0.39 <u>+</u> 0.77	0.87 <u>+</u> 0.69	0.85 <u>+</u> 0.69
Y <u>+</u>	0.48 <u>+</u> 0.59	0.74 <u>+</u> 0.65	3.24 <u>+</u> 0.59	3.29 <u>+</u> 0.59

## **5.2.2.3 Triple-line Source Phantom**

Figure 31 shows the center coordinates data for the three line sources of the Triple-Line Source phantom using the Maximum-Pixel Value method. Table 20 reports the measured alignment errors for the different PET acquisitions relative to the CT data. Again, 3D acquisitions generally show larger alignment errors than the 2D acquisitions. Both the x and y coordinate errors measured for the 3D acquisitions using this method are substantially larger than those using the Manual method. The error in the x coordinates is smaller compared to the errors in the y coordinates.

□СТ



## 5.2.2.4 Triple-Line Source Phantom Rotated by $45^\circ$

Figure 32 gives the PET/CT alignment test data obtained for the Triple-Line Source phantom rotated by 45°. Table 21 provides the measured alignment errors for different PET/CT acquisitions. Combining the alignment errors in x and y coordinates for all the line sources, the average alignment error for all the acquisitions is on the order of 1 mm except for the y-coordinates with 3D acqui



Diameter of sphere (mm)	Alignment error	2D		3D	
	(mm)	Attenuation Correction	No Attenuation Correction	Attenuation Correction	No Attenuation Correction
18 mm	X1 <u>+</u>	1.17 <u>+</u> 0.25	0.6 <u>+</u> 0.21	2.59 <u>+</u> 0.30	2.44 <u>+</u> 0.39
1011111	Y1 <u>+</u>	2.37 <u>+</u> 0.29	2.05 <u>+</u> 0.17	3.03 <u>+</u> 0.08	2.76 <u>+</u> 0.12
12 mm	X2 <u>+</u>	0.13 <u>+</u> 0.15	0.63 <u>+</u> 0.61	1.19 <u>+</u> 0.30	1.49 <u>+</u> 0.20
12 11111	Y2 <u>+</u>	1.49 <u>+</u> 0.12	1.35 <u>+</u> 0.31	3.25 <u>+</u> 0.15	3.28 <u>+</u> 0.16
6 mm	X3 <u>+</u>	0.06 <u>+</u> 0.29	0.22 <u>+</u> 0.29	0.68 <u>+</u> 0.60	0.94 <u>+</u> 0.66
	Y3 <u>+</u>	1.33 <u>+</u> 0.26	0.08 <u>+</u> 0.57	2.43 <u>+</u> 0.31	1.62 <u>+</u> 0.27
8 mm	X4 <u>+</u>	0.44 <u>+</u> 0.21	0.31 <u>+</u> 0.23	1.72 <u>+</u> 0.09	1.72 <u>+</u> 0.09
	Y4 <u>+</u>	1.21 <u>+</u> 0.16	1.63 <u>+</u> 0.17	2.23 <u>+</u> 0.23	2.56 <u>+</u> 0.28
Average	<i>X</i> <u>+</u>	0.45 <u>+</u> 0.31	0.44 <u>+</u> 0.23	1.55 <u>+</u> 0.67	1.65 <u>+</u> 0.63
	<u><u> </u></u>	1.60 <u>+</u> 0.60	1.28 <u>+</u> 0.54	2.74 <u>+</u> 0.76	2.56 <u>+</u> 0.70

Table 22: Measured PET/CT alignment errors for the hot sphere phantom using the Maximum-pixel value method

## **5.2.3 Results from Curve-fitting Method**

## 5.2.3.1 Modified Gammex Phantom with Acrylic Insert

Figure 34 presents the PET/CT alignment test data for the modified Gammex phantom with acrylic insert using the Curve-fitting method. Table 23 records the measured alignment errors for the different PET acquisitions relative to the CT data. Similar to the other two methods, y-coordinate errors for 3D acquisitions were larger than that of the x-coordinate errors. The alignment errors measured using the Curve-fitting method show similar variation as those measured with the other methods.







Table 24: Measured PET/CT alignment errors values for the modified Gammex phantom with solid water insert using the Curve-fitting method

	2	2D	3D	
(mm)	Attenuation Correction	No Attenuation Correction	Attenuation Correction	No Attenuation Correction
X <u>+</u>	2.25 <u>+</u> 0.33	2.30 <u>+</u> 0.33	3.09 <u>+</u> 0.33	3.13 <u>+</u> 0.33
Y <u>+</u>	3.29 <u>+</u> 0.23	3.24 <u>+</u> 0.23	4.82 <u>+</u> 0.22	4.81 <u>+</u> 0.22

### 5.2.3.3 Triple-Line Source Phantom

Figure 36 shows the PET/CT alignment test results for the Triple-Line Source phantom. Table 25 provides the measured alignment errors for the different PET/CT acquisitions. The alignment errors using the 2D acquisitions are larger than the errors using 3D acquisitions. Similar to the Manual method and the Maximum-Pixel Value method, the Curve-fitting method gave smaller errors with smaller uncertainties.





# 5.2.3.4 Triple-Line Source





method gave the least uncertainties using these phantoms where as the Manual method and the Maximum-Pixel Value methods gave similar alignment errors and uncertainties. It is observed that 3D acquisitions gave larger errors than the 2D acquisitions using all the methods.

Diameter	Alignment error	2D		3D	
of sphere (mm)	(mm)	Attenuation Correction	No Attenuation Correction	Attenuation Correction	No Attenuation Correction
19	X1 <u>+</u>	1.15 <u>+</u> 0.21	0.63 <u>+</u> 0.40	2.64 <u>+</u> 0.44	2.08 <u>+</u> 0.39
10	Y1 <u>+</u>	3.31 <u>+</u> 0.23	4.09 <u>+</u> 0.69	4.22 <u>+</u> 0.18	4.31 <u>+</u> 0.18
12	X2 <u>+</u>	0.93 <u>+</u> 0.23	0.75 <u>+</u> 0.29	1.99 <u>+</u> 0.23	2.02 <u>+</u> 0.23
	Y2 <u>+</u>	3.65 <u>+</u> 0.23	3.75 <u>+</u> 0.29	5.00 <u>+</u> 0.23	4.95 <u>+</u> 0.23
6	X3 <u>+</u>	1.43 <u>+</u> 0.40	1.72 <u>+</u> 0.39	1.71 <u>+</u> 0.67	2.22 <u>+</u> 0.60
0	Y3 <u>+</u>	2.91 <u>+</u> 0.16	2.83 <u>+</u> 0.16	4.01 <u>+</u> 0.28	3.74 <u>+</u> 0.23
8	X4 <u>+</u>	0.59 <u>+</u> 0.16	0.55 <u>+</u> 0.17	1.93 <u>+</u> 0.16	1.87 <u>+</u> 0.16
	Y4 <u>+</u>	2.36 <u>+</u> 0.16	2.59 <u>+</u> 0.15	3.17 <u>+</u> 0.34	3.59 <u>+</u> 0.31
				-	-

Table 27: Measured PET/CT alignment errors for the hot sphere phantom using the Curve-fitting method






2D AC 2D No AC 3D AC 3D No AC





Figure 41: Measured alignment errors for the Triple-line Source phantom using (a) the Manual method, (b) the Maximum-Pixel Value method, and (c) the Curve-fitting method.

Figure 42 provides the PET/CT alignment test results measured for the Hot Sphere phantom using the three analyzing methods. All the three methods gave similar alignment errors in the x-coordinate except that of the Maximum-Pixel Value method which gave larger uncertainties. The Curve-fitting method gave larger alignment errors in the y-coordinate than the other two methods.

diameter line sources should provide the most accurate resolution measurement. However, the measured size of the line sources is somewhat larger than one would expect from the manufacturer's specifications for this scanner. The measured sizes for the largest spheres are actually smaller than the nominal object size, which seems incongruous. The results for the 6-mm and 8-mm diameter objects, however, seem more consistent with an expected resolution of ~5 mm FWHM. For instance, for the 8-mm cavity of the acrylic insert, an estimate of PET resolution is given from Equation 3 (p.29) as

$$\sqrt{(9.5mm)^2 - (8mm)^2} = 5.1 \text{ mm}$$
 (Equation 4)

A possible explanation is that an iterative reconstruction algorithm was used to reconstruct the PET images, rather than filtered backprojection. Filtered backprojection is usually recommended for doing resolution measurements; however, for routine QC, one should use the reconstruction method commonly used for patient data, which is iterative reconstruction in this case. Depending on the implementation of the iterative algorithm, the reconstructed images could be converging to produce apparently similar object sizes for the different objects. Further investigation of this behavior is probably warranted, particularly if one hopes to use PET data in conjunction with CT data to help with drawing tumor boundaries for treatment planning.

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### Table 28: Average measured object size for different phantoms using the Curvefitting method to determine the resolution

Phantom	Object size (diameter)	Average measured object size (FWHM)	
Acrylicinsert	8 mm	9.5 mm	
Solid water insert	8 mm	9.45 mm	
Triple-line source phantom	1 mm	7.2 mm	
Hot sphere phantom	6 mm	7.8 mm	
	8 mm	9.24 mm	
	12 mm	8.57 mm	
	18 mm	11.58 mm	



### **CHAPTER 6**

# SUMMARY AND CONCLUSIONS

The primary purpose of this study was to determine if a CT QA phantom could be modified to allow assessment of PET/CT alignment, without altering the quality of CT QA results. The Gammex 464 CT QA phantom was modified to allow the insertion of a radioactive PET marker. The phantom was evaluated for its ability to measure PET/CT alignment and PET resolution in addition to its routine CT quality assurance testing. Two dedicated radioisotope imaging phantoms were also evaluated for PET/CT alignment QA.

CT quality assurance tests were performed on the unmodified Gammex phantom using the ACR-recommended methods. Then these tests were performed on the modified Gammex phantom. The CT QA results were compared to check for the impact of modification on the QA tests. We observed that the modification had little impact on CT QA results. The modified Gammex phantoms with acrylic insert and solid water insert gave similar results as the unmodified phantom. A summary of the results obtained for different CT parameters using the three different Gammex phantoms is provided in Table 29. Except for the CT number calibration of acrylic in the unmodified phantom, which was slightly out of range, the results were within the range prescribed in the Instruction Manual for the Gammex phantom.

PET/CT alignment was measured using three methods for determining the centers of the objects in the images. Using each method, the center coordinates were obtained for the CT and PET images, and the alignment error between them was calculated. We found that although the Manual method produced small alignment errors, the results depend on the user's capability in selecting points for drawing a profile across the source and hence detecting the center coordinates. The Manual method was difficult to use with the Gammex phantom with solid water insert because it was difficult to distinguish between the edge of the insert and the surrounding phantom material, which is also solid water. Thus using insert materials of a different density is advantageous to overcome this difficulty. The Maximum-Pixel Value method was faster than the other methods, but some skill is required in selecting the images to be analyzed. In particular, one must select images that have all sources visible. The Curve-fitting method is the least subjective method and it provides measured PET resolution as well as alignment error.

CT Parameter tested	Unmodified Gammex Phantom	Modified Gammex Phantom with acrylic Insert	Modified Gammex Phantom with solid water insert
CT number calibration	CT number for acrylic slightly out of range	All materials within the given range	All materials within the given range
Slice Thickness (2.5 mm, 5 mm, 7.5 mm at 120 kVp)	2.75 mm, 5 mm, 7.25 mm at 120 kVp	2.5 mm, 5 mm, 7.5 mm at 120 kVp	2.5 mm, 5 mm, 7.5 mm at 120 kVp
Low contrast resolution	6 mm cylinders visible	6 mm cylinders visible	6 mm cylinders visible
High Contrast resolution	7 lp/cm visible	7 lp/cm visible	7 lp/cm visible
Uniformity	2 HU	3 HU	2 HU

Table 29: Results obtained for different CT parameters using the three CT QA phantoms

The results using the Manual method for the Gammex phantom with the solid water insert and the acrylic insert gave comparable results. But, considering the difficulty

in using the modified Gammex phantom with the solid water insert, the modified Gammex phantom with the acrylic insert is the better choice for this method. Also, the triple line source phantom without any rotation gave smaller errors compared to the other phantoms using the Manual method. The results using the Maximum-Pixel Value method for the modified Gammex phantom with solid water insert gave less error than the other phantoms using this method but it also gave large uncertainties of these errors. Using the Curve-fitting method gave worse results for all the phantoms other than the Triple-line Source phantom and the modified Gammex phantom with acrylic insert when compared to the other methods. Considering the amount of time consumed for getting the results using the Manual method, the Maximum-Pixel Value method is a better routine choice as it is faster than the other methods. Also, considering the difficulties in using the solid water insert for the modified Gammex phantom, the modified Gammex phantom with the acrylic insert is a better choice for measuring PET/CT alignment errors.

In the future, obtaining a solid radioactive source, such as sodium 22, for the modified Gammex phantom may be desired. For a solid source, the chance of leaking of radioactive materials is minimized and a Na-22 source can be utilized for longer span of time because of the long half life of Na-22 compared to the 110-minute half-life of F-18. However, using F-18 simplifies issues such as storage of the radioactive insert between QA sessions.

For future insert designs, it is not completely clear whether making the source

objects are preferred to larger objects. A series of tests of inserts with different cavity sizes for the radiotracer would probably be helpful to address this question.

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# **APPENDIX** A

# **IDL PROGRAMS FOR MANUAL METHOD**

1. This program uses a built in function PROFILE to draw profiles between the selected

points for CT images.

pro ctt1
!p.multi[2] = 4
!p.charsize=1.5
!x.style = 3
window, 0, xsize=512, ysize=512

### **APPENDIX B**

# IDL PROGRAMS FOR MAXIMUM-PIXEL VALUE METHOD

1. This is the main program which uses several sub-routines such as CT\_X and CT\_Y to measure the center of the objects in a selected region given as input. X\_LOW, X\_HIGH, Y\_LOW and Y\_HIGH are given as input to describe the region of interest in the CT image. X and Y are given as input to select the range of images to be considered for analyzing.

```
pro TRIAL ct tlsp rotn
!p.multi[2] = 4
!p.charsize=1.5
!x.style = 3
OPENW,1, 'C:\Documents and Settings\prashanth\Desktop\point.txt'
read,PROMPT='Enter X LOW :',X_LOW
read, PROMPT='Enter X HIGH :', X_HIGH
read, PROMPT='Enter Y LOW :', Y_LOW
read, PROMPT='Enter Y HIGH :', Y_HIGH
read,PROMPT='Enter X:',X
read, PROMPT='Enter Y:',Y
x=fix(x)
y=fix(y)
for i=X,Y do begin
    IMAGE='F:\ISGARS\0\'+string(i)
    words = STRSPLIT(IMAGE, ' ', /EXTRACT)
    CT IMAGEPATH=words[0]+words[1]
printf,1,CT_IMAGEPATH,'(',CT_X(CT_IMAGEPATH,X_LOW,X_HIGH,Y_LOW,Y_HIGH),'
,', CT Y(CT IMAGEPATH, X LOW, X HIGH, Y LOW, Y HIGH), ')
endfor
close,1
!p.multi = 0
end
```

2. A sub-routine CT\_X is called in the main program. This sub-routine uses the inputs

4. This is the main program which uses several sub-routines such as PET\_X and PET\_Y to measure the center of the objects in a selected region given as input. X\_LOW, X\_HIGH, Y\_LOW and Y\_HIGH are given as input to describe the region of interest in the PET image. X and Y are given as input to select the range of images to be considered for analyzing.

pro TRIAL\_pet

```
k=i
         i=10.0
         j=10.0
         ENDIF
    endfor
endfor
for i=R,M-1.0 do begin
    for j=S,N-1.0 do begin
         if C[i,j] GT X then begin
         l=i
         i=1000.0
         j=1000.0
         ENDIF
    endfor
endfor
x PET 256=(1+(k-1)/2)
R\overline{E}TUR\overline{N}, x\_PET\_256
END
```

6. A sub-routine PET\_X is called in the main program. This sub-routine uses the inputs

given in the main program and measures the center coordinates in Y of the objects of

interest of PET images using several built-in functions.

```
FUNCTION PET_Y,IMAGEPATH,R,M,S,N
A=read_dicom(IMAGEPATH)
magnifiedImg = CONGRID(A, 614, 614, /INTERP)
C=intarr(564,566)
C=magnifiedImg[49:613,47:613]
X=0.60*MAX(C)
```

## **APPENDIX C**

# **IDL PROGRAMS FOR CURVE-FITTING METHOD**

 This is the main program utilizing sub-routines such as tlsp\_ct\_x and tlsp\_ct\_y to evaluate the center coordinates of the objects in a selected region given by X\_LOW, X\_HIGH, Y\_LOW and Y\_HIGH values. The range of images to be considered for the analysis is given by X and Y values.

PRO tlsp ct fit !p.multi[2] = 4 !p.charsize=1.5 !x.style = 3OPENW,2,'C:\Documents and Settings\prashanth\Desktop\point1.txt' read, PROMPT='Enter X LOW :', X LOW read, PROMPT='Enter X HIGH :', X\_HIGH read, PROMPT='Enter Y LOW :', Y LOW read, PROMPT='Enter Y HIGH :', Y HIGH read,PROMPT='Enter X:',X read, PROMPT='Enter Y:',Y x=fix(x)y=fix(y)for i=X, Y do begin IMAGE='F:\ISGARS\0\'+string(i) words = STRSPLIT(IMAGE, ' ', /EXTRACT) CT IMAGEPATH=words[0]+words[1] printf,2,CT IMAGEPATH, '(',tlsp ct x(CT IMAGEPATH,x low,x high,y low,y hi gh),tlsp ct y(CT IMAGEPATH,x low,x high,y low,y high),')' endfor close,2 !p.multi = 0end

2. This subroutine uses the several built-in and custom made functions for analyzing the

center coordinates of the objects of CT images.

```
for i=0,11 do begin
   for j=0,11 do begin
    difference[i,j]=mask12[i,j]-A[m+i,n+j]
   endfor
endfor
avg=average1(difference)
if(avg lt 5.0)and(avg gt -5.0)crence[i,j]=mask12[i,j]-A[m+i,n+j]
```

```
a=read_dicom('F:\ISGARS\0\450')
mask=fltarr(12,12)
mask[0:11,0:11]=a[174:185,236:247]
return,mask
END
```

5. This subroutine measures the average value on the array, difference, and returns this

value to the tlsp\_ct\_x and tlsp\_ct\_y subroutines.

```
function average1,difference
sum=0.0
average=0.0
for i=0,11.0 do begin
        for j=0,11.0 do begin
            sum=sum+difference[i,j]
        endfor
average=sum/144.0
return,average
end
```

6. A main program, FIT\_resitn, fits a guassian curve to given input parameters using the

subroutines trial\_fit and trial\_fit\_y to obtain the fitted parameters which give the center

coordinates of the object of interest.

```
pro FIT_resltn
!p.multi[2] = 4
!p.charsize=1.5
!x.style = 3
OPENW,1,'C:\Documents and Settings\prashanth\Desktop\point.txt'
read, PROMPT='Enter X LOW :',X_LOW
read, PROMPT='Enter X HIGH :',X_HIGH
;X_HIGH=X_LOW+19.0
read, PROMPT='Enter Y LOW :',Y_LOW
read, PROMPT='Enter Y HIGH :',Y_HIGH
;Y_HIGH=Y_LOW+19.0
read, PROMPT='Enter X:',X
read, PROMPT='Enter Y:',Y
```

```
close,1
!p.multi = 0
end
```

7. Subroutine, resitn utilizes the Guassian

8. Subroutine, trial\_fit utilizes the Guassian curve fit function in the IDL and determines the value of the standard deviation as a fitted parameter which can be utilized for measuring the center coordinates in X of the objects in the PET images.

```
FUNCTION trial fit, PET IMAGEPATH 256, X LOW, X HIGH, Y LOW, Y HIGH
; Define the independent variable.
n = 20
x = FLOAT(INDGEN(20))
; Define the coefficients.
a = [1.0, 9.0, 0.5]
;print, 'Expected: For X Co-ordinate ', a
z = (x - a[1])/a[2]; Gaussian variable
                       ; set up 2x2 plot window
!P.MULTI = [0, 2, 2]
nterms=3
s=read dicom(PET IMAGEPATH 256)
;magnifiedImg = CONGRID(s, 614, 614, /INTERP)
;;C=intarr(564,566)
;C=intarr(512,512)
;;C=magnifiedImg[49:613,47:613]
;C=magnifiedImg[50:564,50:564]
b=fltarr(20)
k=0
for i=X LOW, X HIGH do begin
    for j=Y LOW, Y HIGH do begin
b[k]=b[k]+s[i,j]
    endfor
k=k+1
endfor
v=b
;print,y
y = y + a[0] * exp(-z^2/2)
;print,y
; Fit the data to the function, storing coefficients in
 coeff:
yfit = GAUSSFIT(x, y, coeff, NTERMS=nterms)
;print, 'Result:FOR X ', coeff[0:nterms-1]
; Plot the original data and the fitted curve:
;window, 0, xsize=800, ysize=500
;PLOT, x, y, TITLE='nterms='+STRTRIM(nterms,2),color=255*256L
;window, 1, xsize=800, ysize=400
;OPLOT, x, yfit, THICK=2
RETURN, coeff[1] +X LOW
End
```

9. Subroutine, trial\_fit utilizes the Guassian curve fit function in the IDL and determines the value of the standard deviation as a fitted parameter which can be utilized for measuring the center coordinates in Y of the objects in the PET images.

11. This subroutine creates a square template of same pixel value as that of spherical

#### object 3 of the Hot Sphere phantom.

```
function MASK_spheres_3,x_low
a=x_low
point3=fltarr(7,7)
point3[0,0:6] = [0,0,0,0,0,0,0]
point3[1,0:6] = [0,0,0,123,141,120,0]
point3[2,0:6] = [0,0,145,261,316,209,117]
point3[3,0:6] = [0,107,193,451,590,356,134]
point3[4,0:6] = [0,0,170,398,531,331,134]
point3[5,0:6] = [0,0,120,202,258,193,116]
point3[6,0:6] = [0,0,0,117,134,115,0]
return,point3
END
```

12. This subroutine creates a square template of same pixel value as that of spherical

object 2 of the Hot Sphere phantom.

```
function MASK_spheres_2,x_low
a=x_low
point2=fltarr(8,8)
point2[0,0:7] = [0,0,0,0,0,0,0,0]
point2[1,0:7] = [0,0,0,0,0,0,0]
point2[2,0:7] = [0,0,118,134,118,0,0,0]
point2[3,0:7] = [0,107,187,294,257,150,0,0]
point2[4,0:7] = [0,137,332,586,496,222,109,0]
point2[5,0:7] = [0,132,326,570,481,208,110,0]
point2[6,0:7] = [0,104,177,265,239,141,0,0]
point2[7,0:7] = [0,0,103,130,124,0,0,0]
return,point2
END
```

13. This subroutine creates a square template of same pixel value as that of spherical

object 1 of the Hot Sphere phantom.

```
function MASK_spheres_1,x_low
a=x_low
point1=fltarr(6,6)
point1[0,0:5] = [0,0,0,0,0,0]
point1[1,0:5] = [101,0,0,0,0,0]
point1[2,0:5] = [168,160,118,0,0,0]
point1[3,0:5] = [410,396,190,108,0,0]
point1[4,0:5] = [558,548,241,106,0,0]
point1[5,0:5] = [331,331,176,0,0,0]
return,point1
END
```

14. This subroutine creates a square template of same pixel value as that of solid water

insert of the modified Gammex phantom with solid water insert.

```
function MASK gam SW, x low
a=x low
point=fltarr(16,16)
point[0,0:15] = [10,3,-5,-9,1,5,19,17,13,7,1,7,3,-2,-9,2]
point[1,0:15] = [2,-5,-10,3,19,21,18,13,16,13,15,19,14,5,-19,-1]
point[2,0:15] = [-11,-8,10,22,29,24,18,10,17,15,19,21,16,12,-3,-4]
point[3,0:15] = [-7,2,27,23,18,19,18,7,12,15,18,26,15,13,12,-1]
point[4,0:15] = [-7,16,30,15,11,26,26,13,18,19,18,23,22,21,18,8]
point [5,0:15] = [2,15,15,12,10,31,27,17,16,16,19,20,23,19,14,12]
point[6,0:15] = [14,14,14,20,14,20,6,6,4,-1,11,18,15,13,17,22]
point[7,0:15] = [7,22,27,24,19,14,-2,6,-1,-8,6,15,9,8,18,19]
point[8,0:15] = [10,26,20,21,25,24,8,11,-4,-3,15,25,24,17,20,14]
point[9,0:15] =[6,25,17,24,25,23,11,16,5,10,22,25,27,21,17,8]
point [10,0:15] = [-11,14,17,28,21,16,21,26,19,14,17,20,28,22,14,8]
point[11,0:15] = [-13,3,15,25,23,22,32,29,22,4,10,19,26,23,15,0]
point [12,0:15] = [-12,-7,5,21,29,22,22,22,19,5,18,21,14,17,14,-2]
point [13,0:15] = [-12,-1,-1,9,22,30,21,18,20,27,24,16,8,8,0,-8]
point [14,0:15] = [9,8,-3,-1,10,23,24,20,18,24,21,6,-5,-2,0,-2]
point[15,0:15] = [3,-2,-2,-2,-6,-7,-4,9,-1,0,3,-7,-13,-4,-5,0]
return, point
END
```

15. This subroutine creates a square template of same pixel value as that of acrylic insert

of the modified Gammex phantom with acrylic insert.

```
function MASK_gam_acr,x_low
a=x low
point=fltarr(16,16)
point [0,0:15] = [7,6,15,33,68,106,131,131,129,127,104,73,54,23,2,0]
point [1,0:15] = [16,23,53,93,129,141,139,125,117,127,132,126,118,75,14,2]
point [2,0:15] = [22,56,103,125,140,137,127,130,126,129,136,133,134,117,63,
101
point [3,0:15] = [34,95,126,131,130,125,126,132,129,131,128,129,123,119,110
,43]
point [4,0:15] = [64,127,129,129,135,135,125,112,107,122,129,129,110,112,13
3,79]
point [5,0:15] = [93,132,133,130,136,127,92,52,38,72,111,127,117,124,135,97
point [6,0:15] = [105,124,132,128,122,89,37,4,-3,27,78,121,126,128,132,113]
point [7,0:15] = [119,126,130,129,113,72,19,-4,-2,9,50,107,117,122,134,123]
point[8,0:15] = [111,124,131,137,121,91,23,-6,-2,8,55,110,116,129,134,124]
point [9,0:15] = [83,122,138,143,135,117,64,29,24,43,88,124,124,136,133,117
point [10,0:15] = [721,130,137,130,125,122,119,101,88,104,118,123,122,136,1
26,91]
point [11,0:15] = [41,113,135,124,125,124,130,129,119,127,129,127,125,137,1
23,66]
point [12,0:15] = [15,71,126,133,126,128,125,130,126,129,123,125,129,134,97
,27]
point [13,0:15] = [12,34,86,118,130,133,129,137,138,124,112,128,126,100,37,
-2]
point [14,0:15] = [3,7,31,70,103,123,124,132,131,118,112,116,88,45,0,-6]
point [15,0:15] = [-1,0,-4,11,45,78,88,106,99,82,72,57,27,13,5,1]
return, point
END
```

### VITA

Prashanth K Nookala was born in Hyderabad, India, on October 15, 1978. He attended VNRVJIET, College of Engineering, Jawaharlal Nehru Technological University, Hyderabad, Andhra Pradesh, and received a Bachelor of Engineering degree in Mechanical Engineering in July 2001. He came to United States in January 2002, and started his graduate studies in mechanical engineering at the Louisiana State University, Baton Rouge, Louisiana. During his graduate study he got interested in Medical Physics program at LSU. He joined a master's program in medical physics and health physics at LSU in August 2002. He expects to receive this degree in May 2005.