Application of Chang’s attenuation correction technique for single-photon emission computed tomography partial angle acquisition of Jaszczak phantom

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ABSTRACT

The acquisition and processing of the Jaszczak phantom is a recommended test by the American College of Radiology for evaluation of gamma camera system performance. To produce the reconstructed phantom image for quality evaluation, attenuation correction is applied. The attenuation of counts originating from the center of the phantom is greater than that originating from the periphery of the phantom causing an artifactual appearance of inhomogeneity in the reconstructed image and complicating phantom evaluation. Chang’s mathematical formulation is a common method of attenuation correction applied on most gamma cameras that do not require an external transmission source such as computed tomography, radionuclide sources installed within the gantry of the camera or a flood source. Tomographic acquisition can be obtained in two different acquisition modes for dual-detector gamma camera: one where the two detectors are at 180° configuration and acquire projection images for a full 360°, and the other where the two detectors are positioned at a 90° configuration and acquire projections for only 180°. Though Chang’s attenuation correction method has been used for 360° angle acquisition, its applicability for 180° angle acquisition remains a question with one vendor’s camera software producing artifacts in the images. This work investigates whether Chang’s attenuation correction technique can be applied to both acquisition modes by the development of a Chang’s formulation-based algorithm that is applicable to both modes. Assessment of attenuation correction performance by phantom uniformity analysis illustrates improved uniformity with the proposed algorithm (22.6%) compared to the camera software (57.6%).

Key words: American College of Radiology testing; attenuation correction; single-photon emission computed tomography

Introduction

To evaluate the uniformity, contrast and resolution performance of gamma camera in tomographic mode, acquisition, and processing of a Jaszczak phantom is an important step. The American College of Radiology requires acquisition of the phantom as a part of semi-annual performance testing for tomographic accreditation of a gamma camera. The phantom is filled with 10–20 mCi of technetium-99m (Tc-99m) diluted in water and imaged by the gamma camera in tomographic mode for a certain total number of counts. Attenuation of photons originating from the cylindrical Jaszczak phantom causes artifactual inhomogeneity in the reconstructed count distribution as a function of radial distance with appearance of reduced counts at the center and an increase in counts toward the periphery [Figure 1]. This is caused by the increased attenuation of photons originating from the center of the phantom compared with those originating near the periphery. Chang’s method is a well-established

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attenuation correction technique, originally derived for attenuation correction of uniform attenuating media in 1978 that remains applicable for evaluating modern gamma cameras.\(^3\) Though producing fairly uniform cylinder with constant attenuation for full angular acquisitions (360°), the results are less than satisfactory for partial angle (180°) acquisitions as used for cardiac single-photon emission computed tomography (SPECT) imaging [Figure 2]. Thus, this work explores the plausibility of applying Chang’s attenuation correction for partial angle acquisition of the Jaszczak phantom.

The protocol related to the organ imaged by the gamma camera dictates the acquisition geometry of the camera. Two such geometries that dual-detector gamma cameras commonly use are the full angle acquisition, 360° angular coverage by the detectors with the detectors in 180° opposed configuration [Figure 3a] and the other is a 180° acquisition (where angular acquisition is 180° for imaging the heart) with the detectors in a 90° geometry [Figure 3b]. For cardiac SPECT imaging, 180° acquisition orbit is considered standard. The guidelines from American Society of Nuclear Cardiology specify that 180° circular acquisition orbit yields higher image contrast than 360° acquisition orbit.\(^4\) Numerous previous works explore the comparative performance of 180° and 360° acquisitions for Tl-201 nuclear cardiac imaging, thus paving the path of routine 180° acquisition for nuclear cardiac imaging in the clinic.\(^5\)\(^-\)\(^8\)

By comparing the application of Chang’s attenuation correction on reconstructed Jaszczak phantom images acquired in 180° and 360° angles, optimal results were obtained for 360° acquisition [Figure 2a] while the results were suboptimal for 180° angular acquisition [Figure 2b]. This work investigates whether Chang’s original technique suffices for attenuation correction of Jaszczak phantom image obtained by 180° and 360° angular coverage of the phantom by the detectors.

![Figure 1: A transaxial slice from the cold sphere region of a reconstructed Jaszczak phantom with filtered backprojection reconstruction and Butterworth prereconstruction filter (order: 6 cutoff: 0.55) is illustrated. The count profile illustrates increased counts at the periphery compared to the center due to the greater distance the photons emitted from the central region must travel on average before reaching the detector through the attenuating medium than the periphery.](image1)

**Methods**

**Phantom acquisition and reconstruction**

The deluxe flangeless Jaszczak phantom\(^1\) with solid spheres and solid rods was filled with water and 20 mCi of Tc-99m and mixed well for uniform distribution of radioactivity. Care was taken that no air bubbles were left in the phantom. The phantom was placed in the patient table of Siemens e.cam\(^\text{TM}\) and Siemens Symbia\(^\text{TM}\) (Siemens Healthcare GmbH, Henkestr. 127, 91052 Erlangen, Germany) \((n = 1)\) dual-head gamma cameras centered both in lateral and axial directions.\(^9\)\(^,\)\(^10\) A total of 3 scans were done at 180° orbit acquisition mode and 2 scans at 360° orbit acquisition mode. Thirty-two million counts were acquired for both 360° and 180° orbit acquisition modes.

For 180° orbit acquisition mode, detectors were placed at 90° rotating from left lateral to right lateral position [Figure 3b] which allowed acquisition of 180° projection data with 90° gantry rotation. The detectors were placed at 20 cm from the center of the gantry and counts were acquired for 60 angular projections (3° angular sampling) in step and shoot mode with 32 million counts acquired in total in a circular orbit. The time of acquisition for each projection is calculated by dividing the 32 million counts by the count rate (counts/second) of the detectors and the total number of projections (60) with the phantom in the field of view. A 15% energy window was used, and the images were acquired in 128 × 128 acquisition matrix with a zoom of 1.45.
For 360° orbit acquisition mode, detectors were placed in the 180° [Figure 3a] which allowed acquisition of 360° projection data with 180° gantry rotation. To improve image quality, a noncircular orbit is selected for acquisition allowing the detectors to come as close to the phantom for improved resolution and contrast performance. The images were acquired in step and shoot mode for 128 projection angles (2.8° angular sampling) with 250 K counts acquired at each projection for a total of 32 million counts. A 15% energy window was used, and the images were acquired in 128 × 128 acquisition matrix with a zoom of 1.45.

Reconstruction of the projection data was performed using the filtered backprojection technique available in the e.cam software. A Butterworth filter (order: 6, cutoff: 0.55) was applied to the projections obtained from both acquisitions. Reconstructed transaxial slices were attenuation corrected by Chang’s attenuation correction technique as implemented in the camera software. Reconstructed noncorrected images were also attenuation corrected by a modified Chang’s attenuation correction technique.

**Chang’s equation**

For a point source at coordinates \((x_0, y_0)\) within a material of uniform linear attenuation coefficient \((\mu/\text{cm})\), Chang\(^{[11]}\) defined the attenuation correction factor for recovering counts attenuated by the intervening material by Equation 1.

\[
c(x_0, y_0) = \frac{1}{M} \sum_{i=1}^{M} \exp(-\mu l_i)
\]  

(1)

Where M is the total number of projections in a 360° scan and \(l_i\) is the distance of the point source \((x_0, y_0)\) to the boundary of the surface at projection angle \(\theta\) [Figure 4]. Correction of the reconstructed image with the above attenuation factor is the first-order correction referred as Chang’s order 0. In the successive step, the first-order corrected image is forward projected using an attenuating media and is subtracted from original projected image to obtain an error projection. The error projection is back projected, and first-order corrected and added to the original first-order corrected image. The image thus obtained is second-order correction and referred as Chang’s order 1. This process can be repeated for increased orders. In a modified technique called Moore’s method which is same as Chang’s method for first-order correction, a damping factor is multiplied to the reconstructed error image before adding to the first-order corrected image to obtain the reconstructed second-order corrected image. \(^{[11]}\) This reduces the least square error between original projection and re-projection from next iteration. Both methods were shown to improve attenuation correction accuracy for 360° acquisition with fewer iteration (1–2 iterations) while for 180° acquisition, Moore’s method was more accurate. The comparison of forward projection data with the acquired projection data requires the availability of the original projection data which is inaccessible without vendor intervention, thus the only attenuation correction technique used for this work is Chang’s order 0 which is also the only technique available in the camera software.

**Defining attenuation path length for each angle**

For estimating the attenuation correction factor \((l_i\) in Equation 1) for all angles around the phantom (number of angular samples \(M\)'), the attenuation path length is defined in this study for each point locations \((x_0, y_0)\) inside the phantom. Initially, the phantom center \((x_c, y_c)\) and radius \((r)\) is defined from the transaxial slice of the Jaszczak phantom with Imagej software.\(^{[12]}\) The boundary points of the Jaszczak phantom image were defined by the pixels whose coordinates \((x_i, y_i)\) satisfies Equation 2.

\[
\left(\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} - r\right) < 0.5
\]  

(2)
The boundary points of the circular Jaszczak phantom (total \(M'\)) are considered to represent the 360° arc around the phantom. For all points inside the phantom, the correction factor for attenuation correction of counts at pixel coordinate \((x_0, y_0)\), \(c(x_0, y_0)\), is computed by Equation 3.

\[
c(x_0, y_0) = \frac{1}{M'} \sum_{i=1}^{M'} \exp \left( -\mu \left( \sqrt{(x' - x_0)^2 + (y' - y_0)^2} \right) \right) \quad (3)
\]

As the SPECT projection data system is acquired in broad-beam geometry instead of narrow beam geometry, the attenuation coefficient \(\mu\) utilized (0.12/cm) is less than the attenuation coefficient calculated (0.155/cm) for narrow beam geometry.\(^{11,14}\) The correction factor calculated from Equation 3 is utilized to obtain attenuation corrected image from noncorrected image as illustrated in Figure 5.

The angular span for calculating the attenuation coefficients (Equation 3, \(M'\)) is independent of the angular coverage of the detector around the phantom. That is, \(M'\) in Equation 5 is always spanning 360° angles independent of whether 360° or 180° angular coverage was used for the acquisition. This is different than the current method of calculating attenuation coefficients where \(M'\) is same as \(M\) over the same total angular coverage as those for the acquisition of the phantom contributing to regional inhomogeneity for 180° acquisition [Figure 2b].

**Quantitative evaluation of phantom uniformity**

For evaluating the quantitative accuracy of attenuation correction, integral uniformity and noise of the phantom region from postreconstructed and attenuation corrected images were evaluated. One circular region of interests (ROI) of 20 cm diameter was drawn in average of 5 transaxial slices (total 16.5 mm slice thickness) from the uniform part of the phantom at the center for the reconstructed images obtained from 360° to 180° acquisition. The ROI mean counts (\(Counts_{\text{Mean}}\)), standard deviation (\(Counts_{\text{SD}}\)), highest (\(\text{pixel}_\text{cnt}_{\text{max}}\)) and lowest (\(\text{pixel}_\text{cnt}_{\text{min}}\)) pixel counts were estimated. The intrinsic uniformity is calculated by Equation 4 and noise is calculated by Equation 5.

\[
\text{IntegralUniformity}(\%) = \frac{\text{pixel}_\text{cnt}_{\text{max}} - \text{pixel}_\text{cnt}_{\text{min}}}{\text{pixel}_\text{cnt}_{\text{max}} + \text{pixel}_\text{cnt}_{\text{min}}} \times 100 \quad (4)
\]

\[
\text{Noise}(\%) = \frac{\text{Counts}_{\text{SD}}}{\text{Counts}_{\text{Mean}}} \times 100 \quad (5)
\]

**Results and Discussion**

The attenuation corrected image of the Jaszczak phantom obtained by applying the correction factor (Equation 3) to the non-corrected image is shown in Figure 6 for both (a) 360° and (b) 180° acquisitions. The results illustrate uniform attenuation correction for both acquisitions.

Uniformity and noise analysis results as illustrated in Table 1 demonstrate comparable uniformity and noise for 360° acquired phantom images attenuation corrected by the vendor technique (28.3% and 7.9%) and the proposed technique (26.8% and 8.4%). The difference in uniformity for 180° acquisition between the proposed technique (22.6% and 6.8%) and the vendor technique (57.6% and 30.1%) was more substantial.

Definition of phantom boundary is user-dependent that may make the attenuation correction results subjective. A more robust way is to define the boundary automatically using the weighted 1st or 2nd order derivative. Future work will involve automatic boundary detection of transaxial images making the attenuation correction process user-independent.

**Conclusion**

The Chang’s attenuation correction technique can be used for attenuation correction of noncorrected Jaszczak
phantom image independent of the 180° and 360° angular coverage of the phantom by the detectors.

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Conflicts of interest
There are no conflicts of interest.

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Table 1: Uniformity evaluation of reconstructed Jaszczak phantom acquired in 360° and 180° arcs attenuation corrected by techniques available in the camera software and proposed in this work.

| Acquisition arcs | Intrinsic uniformity (noise) for camera software (%) | Intrinsic uniformity (noise) for proposed technique (%) |
|------------------|------------------------------------------------------|-------------------------------------------------------|
| 180°**           | 57.8 (29.3)                                          | 23.5 (7.8)                                            |
| 180°**           | 53.8 (28.9)                                          | 22.8 (6.1)                                            |
| 180°**           | 61.1 (32.1)                                          | 21.5 (6.5)                                            |
| 360°**           | 29.7 (8.0)                                           | 27.7 (8.4)                                            |
| 360°**           | 26.8 (7.9)                                           | 25.9 (8.4)                                            |
| Averaged uniformity for 180° | 57.6 (30.1)                                           | 22.6 (6.8)                                            |
| Averaged uniformity for 360° | 28.3 (7.9)                                           | 26.8 (8.4)                                            |

*1st Siemens e.cam™ camera, *2nd Siemens Symbia™ camera, 1st Siemens e.cam™ camera with only cardiac acquisition license (only 180° acquisition)