Nuclear Instruments and Methods in Physics Research A 861 (2017) 16–22

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Influence of different path length computation models and iterative reconstruction algorithms on the quality of transmission reconstruction in Tomographic Gamma Scanning

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ARTICLE INFO

Keywords:
Tomographic Gamma Scanning
Quality of transmission reconstruction
Path length simulation models
Maximum Likelihood Expectation Maximization
Algebraic Reconstruction Technique

ABSTRACT

This paper studies the influence of different path length computation models and iterative reconstruction algorithms on the quality of transmission reconstruction in Tomographic Gamma Scanning. The research purpose is to quantify and to localize heterogeneous matrices while investigating the recovery of linear attenuation coefficients (LACs) maps in 200 liter drums. Two different path length computation models so called ”point to point (PP)” model and ”point to detector (PD)” model are coupled with two different transmission reconstruction algorithms - Algebraic Reconstruction Technique (ART) with non-negativity constraint, and Maximum Likelihood Expectation Maximization (MLEM), respectively. Thus 4 modes are formed: ART-PP, ART-PD, MLEM-PP, MLEM-PD. The inter-comparison of transmission reconstruction qualities of these 4 modes is taken into account for heterogeneous matrices in the radioactive waste drums. Results illustrate that transmission-reconstructed qualities of MLEM algorithm are better than ART algorithm to get the most accurate LACs maps in good agreement with the reference data simulated by Monte Carlo. Moreover, PD model can be used to assay higher density waste drum and has a greater scope of application than PP model in TGS.

1. Introduction

Nowadays, a great amount of nuclear radioactive wastes have been generated during the operation of nuclear power stations and other nuclear facilities. The low-level and medium-level (LL & ML) radioactive wastes are usually packed in containers with different sizes, e.g. economical 200 liters national standard drums. These containers must be characterized to meet the strict national legal restrictions, regulations and comply with nuclear safeguards for nuclear material accounting against the International Atomic Energy Agency (IAEA) [1] to create an inventory that waste can be categorized and certified before the interim or long-term storage or disposal.

Traditional methods for assaying waste drums called destructive assay (DA) methods call for opening sealed drums, which requires risky, time-consuming and expensive operations of radiation protection. Therefore, non-destructive assay (NDA) methods, such as segmented gamma scanning (SGS) and tomographic gamma scanning (TGS), have been developed suitable for routinely characterizing radioactive waste drums in terms of computation time, accuracy and reliability requirements without opening sealed drums. Comparing with SGS that assumes the homogeneous matrix and uniform activity, better accuracies can be yielded by TGS in cases that radionuclides are distributed non-uniformly in heterogeneous matrices. The detection process of TGS consists of two stages, which are called transmission reconstruction stage and emission reconstruction stage. The application range of TGS is limited by densities of assayed matrices to make the final emission-reconstructed total activity of the waste drum more or less in-accurate [2], but the accuracy of the emission-reconstructed total activity depends to a large extent on the accuracy of linear attenuation coefficients (LACs) results of the transmission reconstruction in TGS.

In this paper, attention will be paid to explore the quality of transmission reconstruction using two different path length computation models—”point to point (PP)” model, ”point to detector (PD)” model and two different transmission iterative algorithms—Algebraic Reconstruction Technique (ART), Maximum Likelihood Expectation Maximization (MLEM), aiming at choosing the most appropriate path length computation model and transmission reconstruction algorithm.

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http://dx.doi.org/10.1016/j.nima.2017.04.040
Received 12 January 2017; Received in revised form 11 April 2017; Accepted 25 April 2017

2. Theory

Tomographic Gamma Scanning (TGS) was developed by Estep et al. of Los Alamos National Laboratory (LANL) [3], and it subdivides the waste drum into many vertical layers in which every vertical layer is subdivided into many voxels that are assumed to be of homogeneous matrix and uniform activity with sizes usually comparable to the collimator of the well-collimated high purity germanium (HPGe) detector. Meanwhile, a transmission source used for determining LACs of voxels for the reason that the knowledge of the waste LACs is of great significance to correctly evaluate the activities of radionuclides in the waste, is positioned on the opposite side of HPGe detector, with the waste drums standing in the middle. By the way of the rotation and translation of the waste drum, the transmission source used to acquire data grabs for each vertical layer is well-collimated to let the photon beams pass through only one corresponding vertical layer to arrive at the end cap of HPGe detector, so that every vertical layer can be separately dealt with in transmission reconstruction stage.

2.1. Transmission reconstruction stage

The attenuation of γ-rays of a specific energy passing through one vertical layer can be characterized by Beer's Law [4] as follows:

$$N_i = N_0 \exp\left(-\sum_j \mu_j x_{ij}\right) \tag{1}$$

where N_0 is the count rate of the transmission source without any attenuation acquired by HPGe detector; N_i is the count rate in the ith transmission measurement attenuated by the waste drum acquired by HPGe detector; μ_j is the linear attenuation coefficient (LAC) of the jth voxel; x_{ij} is the path length of the μ_j voxel along a ray connecting the transmission source and the detector crystal in the ith measurement. Noting that in this paper, the un-attenuated count rates are obtained with an empty drum and attenuated count rates are obtained with a real waste drum. For the sake of convenience, by considering the empty drum as the blank sample to eliminate the influence of steel waste drum wall, thus the transmittances are determined to only define matrices in a waste drum. In TGS, every layer is measured I times and subdivided into J voxels. The scan ways of TGS are various, and this paper chooses the most basic stepwise way, which is corresponding to M discrete translation positions and I/M discrete rotation positions.

Converting Eq. (1) to logarithmic form

$$-\ln\left(\frac{N_i}{N_0}\right) = T = \sum_j \mu_j x_{ij} \tag{2}$$

As a result, the transmission reconstruction issue can be transformed to solve the discrete linear equations:

$$\mathbf{X} \bullet \mathbf{U} = \mathbf{T} \tag{3}$$

where the size of all voxels path length matrix $\mathbf{X}$ is $I_* J$ and the size of unknown LACs matrix $\mathbf{U}$ is $J_* 1$. The transmission reconstruction quality depends to a certain extent on the system matrix $\mathbf{X}$ mentioned above, which is one of the focuses of this paper and is critical for determining LACs necessarily needed in the next emission reconstruction stage.

2.2. Transmission Reconstruction Algorithms of TGS

Obviously, the transmission reconstruction issue is to find the solutions to the linear systems of equation mentioned above. One main focus of this paper is to test the validity of two transmission reconstruction algorithms — ART algorithm and MLEM algorithm, which are written in C/C++.

2.2.1. ART algorithm

Among various algorithms that can be used to solve the linear system of equations of transmission reconstruction of TGS, ART and its variations are a common choice [5–9]. Its iterative process is given by:

$$\mu_j^{(k+1)} = \mu_j^{(k)} + \frac{x_i^T}{\|x_i\|^2}\left(t_i - x_i t_i^{(k)}\right) \tag{4}$$

where k is the iteration number; $\mu_j^{(k+1)}$ and $\mu_j^{(k)}$ are the new and current estimates, respectively; x_i is the row vector coming from the ith row of the path length matrix $\mathbf{X} = [x_1, x_2, \ldots, x_I]^T$ mentioned above with the size being $1{*}J$ representing the ith ray; t_i is the ith row value of the matrix $\mathbf{T}$ mentioned above; $t_i^{(k)} = \sum_{j=1}^{J} x_{ij}\mu_j^{(k)}$ is the estimated value considering the impact of the ith ray.

2.2.2. MLEM algorithm

MLEM algorithm is an optimization method for finding the best estimate for solution fitting a given criterion that is the maximization of the likelihood of the reconstructed image with minimal structure [10–14]. Therefore, LAC of every voxel can be obtained by solving Eq. (3) by the following iterative formula:

$$\mu_j^{(k+1)} = \left(\sum_{i=1}^{I} \frac{x_{ij}}{\sum_{i'=1}^{I} x_{i'j}} \frac{t_i}{t_i^{(k)}}\right)\mu_j^{(k)} \tag{5}$$

where same letters in the formula is the same as that of Eq. (4).

2.3. Path length computation models of TGS

Note that path lengths in every voxel from different translation and rotation positions are computed using the Cyrus-Beck algorithm [15–17] and geometric parameters. Cyrus-Beck algorithm that is an efficient clipping algorithm for two-dimensional and three-dimensional convex bodies in computer graphics to determine which voxels the rays pass and calculate path lengths of these voxels. As a result, accurate path lengths of real irregular shaped voxels by the drum fringe are acquired, instead of traditional cubic shaped voxels treatment pattern [18–20]. For the purpose of successfully transmission-reconstructing LACs images, Estep et al. [3] simplified the transmission source and the detector in TGS model to be a point source and a point detector without physical dimensions respectively, which is called ”point to point (PP)” model shown in Fig. 1. This is reasonable for those scans performed with a collimated or pencil beam, but in some designs, for example, an open beam filled the detector field of view is used to increase count rate. In this paper, a model named ”point to detector (PD)” model shown in Fig. 2, which assumes the transmission source and detector to be a point source and a real detector.

The path length values of every voxels can be computed easily in the cylinder drum layer in PP model. But for PD model, two perpendicular diameters of Ge crystal face of HPGe detector are subdivided equally into 10 parts to get 88 areas included in the face, but only 80 areas are used with whose corresponding rectangular centers are included in the drums shown in Fig. 2. At each discrete translation and rotation position, distances between 80 center points array and the transmis-

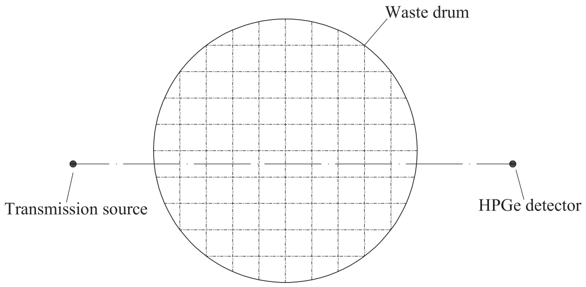

Fig. 1. ”Point to point(PP)” model.