First results on Compton camera system used for X-ray fluorescence computed tomography

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ABSTRACT

Because of the ability to present molecular and functional information in organisms, nuclear medical imaging (NMI) is attracting more and more attention. Among NMI modalities, X-ray fluorescence computed tomography (XFCT) has the advantage that the tracers used in XFCT are not spontaneously decayed. The synthesis, storage of contrast agents is more convenient, the price of XFCT is much lower as well. However, XFCT usually has mechanical collimation to tell the incident photon direction, which results in the reduction of the detection efficiency. The Compton camera is an imaging modality, which does not need mechanical collimators in its structure, which makes Compton cameras have high detection efficiency. Therefore, it is a great idea to use Compton camera-based imaging systems to realize X-ray fluorescence (XF) imaging. In this work, the first XFCC imaging system in the laboratory environment is established, which consists of a 150keV X-ray tube and a single-layer Compton camera system based on the Timepix3 photon-counting detector (PCD). The element Gd (43keV) is used as the XF element. The first imaging reconstruction results of the XFCC system are represented.

Keywords: Compton camera, image reconstruction, X-ray fluorescence computed tomography, Timepix3, photon counting detector

1. INTRODUCTION

Because of the ability to present molecular and functional information in organisms, nuclear medical imaging (NMI) is attracting more and more attention. Compared with traditional NMI modalities like single photon emission computed tomography (SPECT) and positron emission tomography (PET), the X-ray fluorescence computed tomography (XFCT) has the advantage that the tracers used in XFCT are not spontaneously decayed [1, 2]. The synthesis, storage of contrast agents is more convenient, the price of XFCT is much lower as well. SPECT and XFCT, which can use a variety of traces, usually have mechanical collimation to tell the incident photon direction, which results in the reduction of the detection efficiency.

The Compton camera (CC) is an imaging modality that does not need mechanical collimators in its structure [3]. This makes Compton cameras have high detection efficiency. Compton camera has been widely used in astronomical detection, environmental radiation detection, proton therapy, and medical imaging [4-6]. So it is a great idea to use Compton camera-based imaging systems to realize X-ray fluorescence (XF) imaging. However, the imaging of the X-ray fluorescence Compton camera (XFCC) is not easy. A large number of scattered photons enter the detector together with X-ray fluorescence photons, and it is tough to distinguish them. Besides, the commonly used elements of XF imaging are usually below 100keV. The high-resolution reconstruction of Compton cameras is difficult in this energy range.

There are few studies about Compton cameras for XF imaging. Vernekohl et al. carry out the Monte Carlo simulation with the incidence of ideal 82keV monochromatic X-rays and gold nanoparticle (GNPs) solution as the XF element [7]. In this work, the first XFCC imaging system is established in the laboratory environment, which consists of a 150keV X-ray tube and a single-layer Timepix3 detector Compton camera. The element Gd (43keV) is used as the XF element. The first imaging reconstruction results of our XFCC system are represented.

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2. METHODS

2.1 Compton camera

In Compton camera imaging, photons are incident on the first layer of the detector and interact with the detector atoms. The scattering detector will record the interaction position and the deposition energy of recoil electrons. The scattered photons are then emitted from the first lie detector and absorbed by the second layer detector. The absorption detector records the absorption position and the deposited energy. The Compton scattering angle θ is according to the Compton effect formula:

$$cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_0}\right) \tag{1}$$

where E_0 is the energy of the incident photon, E_2 is the energy of the scatted photon, θ is the Compton scattering angle, m_e is the rest mass of the electron. After calculating the scattering angle θ, we are still not sure where the specific incident direction of the incident photon is. But we can build a cone surface with $r_1 r_2$ as the axis and θ as the cone angle, on which we can find the incident direction. When enough Compton scattering events are detected, each event can be inversely calculated to a cone surface. The intersection of these cone surfaces is theoretically the spatial position of the radioactive source, which is the reconstruction principle of the simple back-projection (SBP) algorithm.

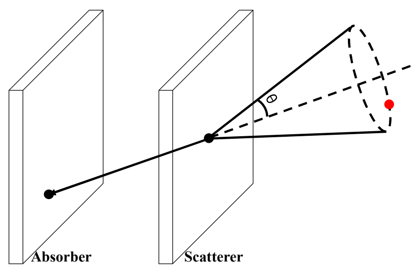

Figure 1. The principle of the Compton camera.

2.2 LM-MLEM reconstruction algorithm

In the SBP algorithm with cone intersection, each incident photon event will be back-projected to all points on a cone surface. So the spatial positions where the source is not located also obtain the weight by mistake, which makes the reconstruction result inaccurate.

The most commonly used high-resolution reconstruction algorithm is the list-mode maximum likelihood expectation maximization (LM-MLEM) algorithm. The iteration formula of LM-MLEM is as follows[8]:

$$\lambda_j^{(l+1)} = \frac{\lambda_j^{(l)}}{s_j} \sum t_{ij} \frac{1}{p_i^{(l)}}, \tag{2}$$

$$with\ p_i^{(l)} = \sum_{k=1}^{M} t_{ik} \lambda_k^{(l)} \tag{3}$$

where $\lambda_j^{(l)}$ is the reconstruction image. t_{ij} is the element of the system matrix, indexed on the events i and the voxels j. s_j is the element of the sensitivity matrix. The system matrix is obtained by our proposed numerical calculation method with detector resolution and Doppler broadening correction. While the sensitivity matrix is obtained by the Monte Carlo simulation method.

2.3 C. Timepix3 data processing

The Compton camera system established by us is based on the single-layer Timepix3 detector[9]. Timepix3 is an advanced photon-counting detector (PCD) with high spatial resolution, high time resolution, and fast readout speed.

The raw data of Timepix3 is the time of arrival (ToA) and time-over-threshold (ToT), which is corresponding to the time and energy information of the interaction event after calibration. The array of 256*256 pixels can give 2-dimensional position information. After time clustering and spatial clustering, the data belonging to the same incident photon can be clustered together, and the charge sharing effect is eliminated.

The information of the z-direction can be obtained by the carrier drift time, which is calibrated by the muon track. Due to the constant carrier drift velocity, the depth of the interaction is proportional to the carrier drift time. After calibration of the carrier drift velocity, the depth difference of the scattering position and the absorbing position can be calculated from the drift time difference. So that all information needed for the Compton camera reconstruction is obtained, including the energy information and the three-dimensional position information. Then coincidence operations are used for the detected interaction signals. And the valid Compton scattering events in the single-layer Timepix3 detector are selected for the SBP and LM-MLEM reconstruction of the proposed Compton camera.

3. EXPERIMENT SETTINGS

The experimental design is shown in Figure 2. The incident X-ray is emitted by a 150kV microfocus X-ray tube with a copper filter. The X-ray is collimated to the fan beam by a tungsten slit and then and then irradiated on the Gd solution. The Timepix3 detector is placed at the location of 90° from the X-ray incident direction.

In all experiments, the X-ray tube is set to 150keV and 0.5mA. The concentration of the Gd solution is 100mg/ml. The Timepix3 detector has 256×256 pixels. The size of the detector unit is equal to 55 μm and the size of the detector is 14.08×14.08 mm2. The detector is with a bias voltage equal to 200V and an energy threshold equal to 3.02keV. The detector temperature is maintained at 26-28°C to keep the carrier drift velocity stable.

There are two groups of experiments, as shown in Figure3. One has a single solution pipe, and another has two solution pipes. The diameter of all the solution pipes is equal to 5mm. The distance between the detector plane and the position where X-ray fluorescence photons emit is 50mm. For each experiment, the acquisition time is 100s. The imaging space is set to 60×60×20 pixels and the pixel size is equal to 4mm. Therefore, the field of view (FOV) is 240×240×80 mm3. The central slice of the FOV is 50mm far away from the detector plane, and the center of the FOV is on the z-axis, which is passing through the center point of the detector and perpendicular to the detector plane.

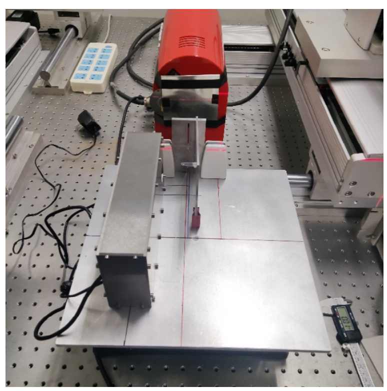

Figure 2. The experiment settings in the laboratory environment.

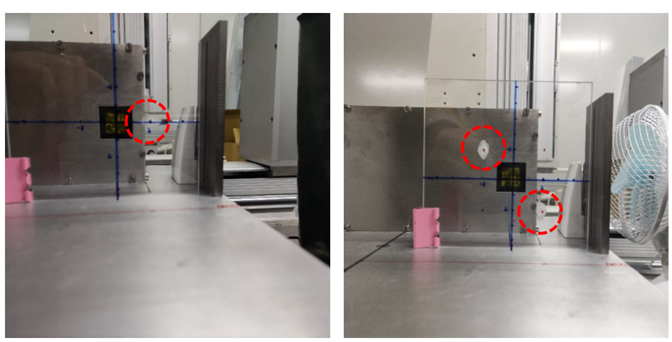

Figure 3. The position of the solution tubes in the two group of experiments respectively.

4. RESULTS AND DISCUSSIONS

After data acquisition of the Compton camera system, the Compton scattering events detected by the Timepix3 detector are selected. These events are used for SBP reconstruction and LM-MLEM reconstruction. The iteration number is 50 and the initial image of the LM-MLEM iteration is the SBP image.

Figure 4 shows the energy spectrum of all photons detected by the XFCC system. The spectrum peak below 20keV represents the photons that incompletely deposit their energy. The two peaks in the range of 40~50keV are the Kα (42.280 keV & 42.983 keV) peak and Kβ (48.718 keV & 49.961 keV) peak of Gd, respectively. The peak around 60keV is the Kα peak of W, while the peak around 65keV is Kβ. This is because many photons go through the tungsten slit and excite these characteristic gammas. From the spectrum, we can know that the proportion of the X-ray fluorescence photons is relatively low, which needs more improvement in our further works.

The reconstruction results of the first experiment prove the correct imaging reconstruction of the XFCC system. The solution pipe is placed at (20,0), which is the out center of the FOV. It is obvious that the SBP algorithm cannot realize a high-resolution reconstruction of the XFCC system at all. The single solution pipe can be clearly distinguished with the LM-MLEM algorithm. The spatial resolution is about 10mm for the single solution pipe.

For the second experiment, the reconstruction of the double solution pipes is also completed with LM-MLEM and there are two circle areas in the result image. However, the voxel value of the two areas is not very consistent, which may be due to the imperfection of system geometric correction and the lack of Compton events. Besides, the reconstruction resolution becomes worse than the single pipe experiment. Multi-source reconstruction is a classic problem in the field of Compton cameras, which is to be overcome in the future. Besides, it is important to help increase the proportion of X-ray fluorescence photons.

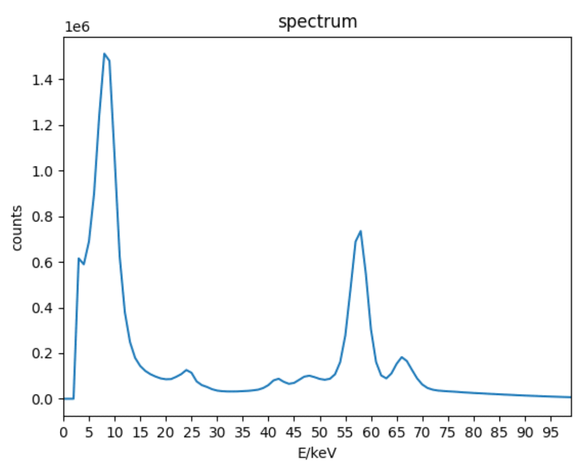

Figure 4. The energy spectrum of the photons detected by the Compton camera system.

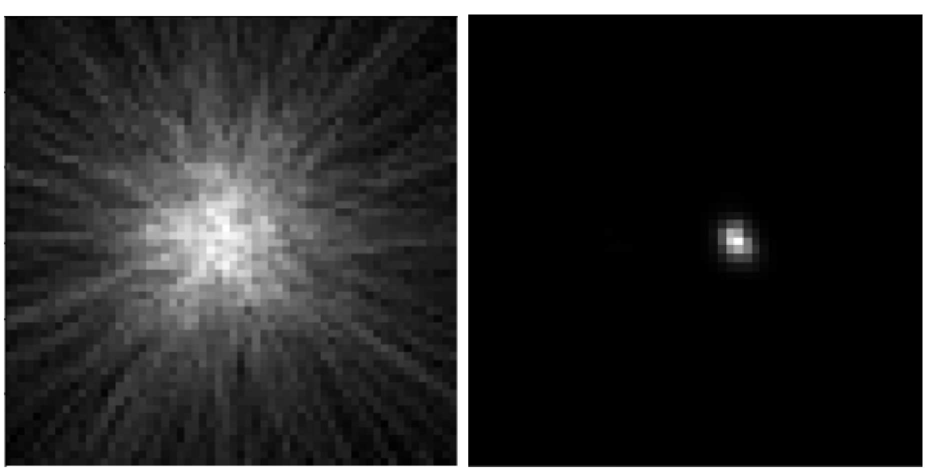
Figure 5. The results of the first experiment.

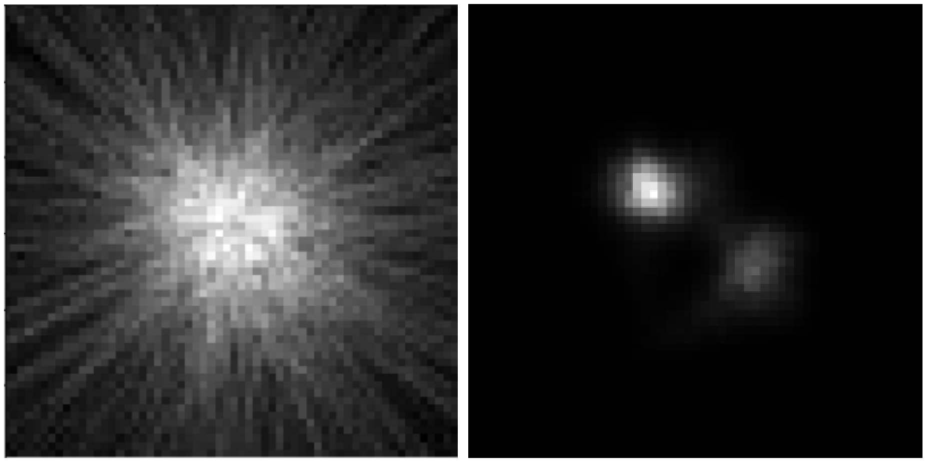

Figure 6. The results of the second experiment.

5. CONCLUSIONS

In this work, we proposed the first XFCC imaging system in the laboratory environment, which consists of a 150keV X-ray tube and a single-layer Timepix3 detector Compton camera. The element Gd (43keV) is used as the XF element. The first results of the XFCC system are represented. Experiments with both single solution pipes and double solution pipes are carried out, and the LM-MLEM reconstruction result images illustrate the spatial resolution of about 10mm. For the double solution pipes experiment, the interaction between multi-sources makes the result not satisfactory enough. Besides, the problem of increasing the proportion of XF photons is still another important problem to be overcome in the future.

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