Gate simulation of Compton Ar-Xe gamma-camera for radionuclide imaging in nuclear medicine

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Abstract. Computer simulations of cylindrical Compton Ar-Xe gamma camera are described in the current report. Detection efficiency of cylindrical Ar-Xe Compton camera with internal diameter of 40 cm is estimated as1-3%that is 10-100 times higher than collimated Anger's camera. It is shown that cylindrical Compton camera can image Tc-99m radiotracer distribution with uniform spatial resolution of 20 mm through the whole field of view.

1. Introduction

Taking all into consideration we conclude that behavior of S-factor in different cases has a strong influence on effective therapeutic activity. Method has high flexibility and reproducibility and gives opportunity to physician for wide retrospective in-depth analysis, thus such approach will lead to improvement of RSO effectiveness.

Radionuclide imaging is a powerful tool for medical diagnostics [1]. Single photon emission computer tomography (SPECT) based on Anger scintillation gamma cameras with typical spatial resolution of about 10 mm is commonly used for imaging distribution of radioisotopes emitting single gamma quanta. However, the low efficiency of mechanically collimated gamma cameras significantly affects their performance, particularly it is not possible to reduced exposition time or to lower the activity of administered radionuclide. The absence of a collimator allows to use much more of the available radiation.

Detectors with an electronic collimation based on the Compton effect, having a high luminosity and an acceptable spatial resolution of ~ 10 mm, were considered in a number of previous studies [3,4]. In the current work parameters of a full size cylindrical gaseous Argon-Xenon Compton gamma camera are optimized through Monte Carlo simulations in Gate/Geant4 environment [2].Also, the requirements for event selection and reconstruction algorithms for 3D Compton images are discussed.

2. Compton gamma camera

The determination of the source location via the Compton effect is based on the dependence between the scattering angle Θ and the energy of the recoil electron E_1 after Compton scattering of a gamma quantum with the energy E:

$$\cos(\theta) = 1 - m_e c^2 \left(\frac{1}{E_1} - \frac{1}{E} \right)$$

Compton camera (see Figure 1) consists of a scatter detector (SD) and an absorption detector (AD). If the energy of the gamma rays is known it is necessary to determine the energy of the recoil electron E1 in the RD for calculation of the scattering angle Θ. Compton gamma camera detects the arrival direction of the gamma ray within the events acceptance cone, which is determined by the scattering angle Θ. Event cone axis is the extension of straight line connecting the point of interaction in the SD (x1, y1, z1) and the AD (x2, y2, z2).The apex of the cone is the point of interaction (Compton scattering) in the RD.

Uncertainty in the determination of the events acceptance cone are defined by a finite energy resolution of the SD, an error in the coordinates of events and by the Doppler broadening of the scattered γ-ray energy [3].
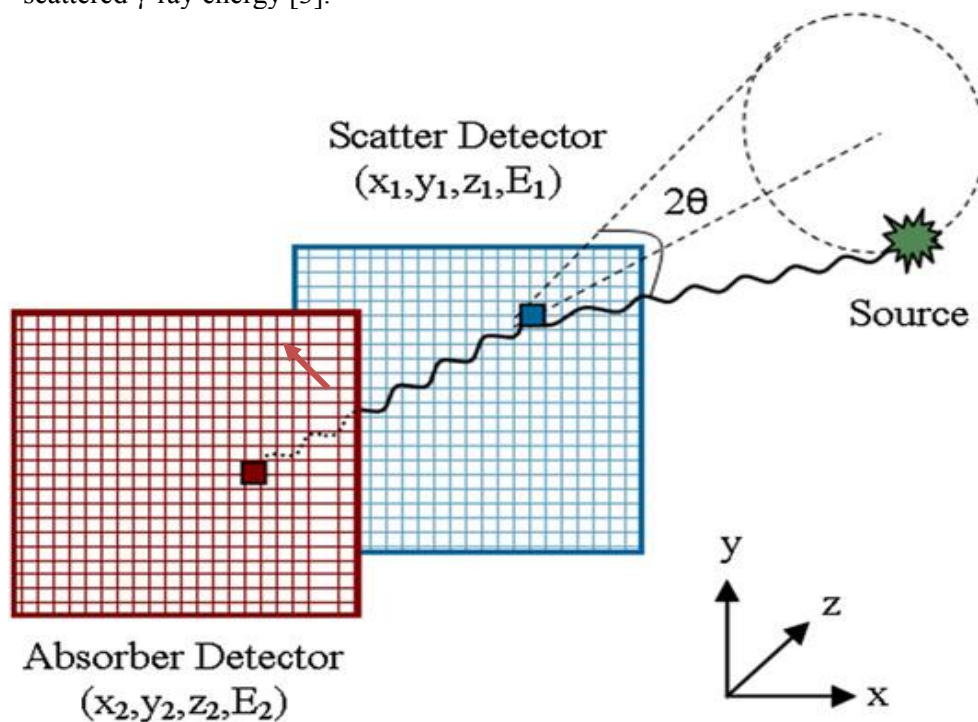

Figure 1. Compton camera operation principle.

3. Optimal parameters of gaseous detectors

3.1.General requirements for the Compton camera detectors
The scatter detector (SD) determines the coordinates of Compton interaction and the energy of Compton electron. SD must have high energy resolution and the prevailing probability of Compton scattering of the gamma rays η_C. The probability of photoelectric effect and multiple Compton scattering should be as low as possible.

Total absorption detector (AD) determines the coordinates and energy of photoelectric absorption. AD should have a high probability of the photoelectric effect η_{PE} for gamma rays. Contributions of single and multiple Compton scattering (followed by photoelectric effect) in AD should be minimal.

The detector for medical imaging should enclose the investigated object in order to achieve maximal efficiency. The optimal geometry of the Compton gamma camera for this task is a coaxial system of two cylinder detectors (SD and AD) of considerable size (about 1 m in diameter and in length). The only economically available detectors with such a size may be gaseous detectors. The aim of the computer simulation is to optimize the parameters of the gaseous scatter and absorber detectors of the Compton gamma camera to obtain the highest possible registration efficiency for gamma rays emitted by radioisotope Tc-99m (140 keV).

3.2. Selection of the optimal parameters of the gaseous detectors
Selection and optimization of parameters of gaseous detectors are carried out through Monte Carlo simulation in Gate\Geant4 environment, and the simulation results were analyzed in the MathLab environment.

The results of simulation have demonstrated that the most suitable gas for the SD is argon (η_C>80%) and for the AD is xenon (η_{PE}> 90%). Required detection efficiency can be achieved by increasing the gas pressure or the thickness of the detector.

Increasing the pressure from 10 bar to 20 bar in the SD at a constant scattering efficiency causes the grow of multiple Compton scattering. The ratio of probabilities of single (η_C) and multiple (η_{MC}) Compton scattering ($\kappa_C = \eta_C / \eta_{MC}$) reduce from 30 to 18. Multiple scattering worsen the quality of the reconstructed image. Optimal parameters for SD gaseous chamber are thickness of about 35 cm and argon pressure of 15 bar. It provides the scattering efficiency $\varepsilon_C = 10$ % and the single/multiple ratio $\kappa_C = 22$.

Similar calculations for the AD have shown that increasing the pressure at the same photoelectric absorption efficiency (η_{Ph}) causes growing the probability of photoelectric effect following Compton scattering (η_{C+Ph}), which also worsen image quality. The ratio of probabilities ($\kappa_{Ph} = \eta_{Ph} / \eta_{C+Ph}$) decreases from ~ 11 to ~ 9 by increasing the pressure from 10 bar to 20 bar. The obtained results demonstrate that the optimal parameters for AD gaseous chamber is a thickness of ~ 30 cm and xenon pressure of 15 bar. This ensure the effectiveness of the photoelectric absorption $\varepsilon_{Ph} = 72\%$ with the accept able contribution of multiple events $\kappa_{Ph}= 9.5$.

3.3. Accuracy of the interaction position determination
Position of Compton scattering or photo absorption events determined by the detector corresponds to the center of ionization region created by the secondary electrons. To estimate the spatial resolution of SD and AD the deviations of event position from the real point of interaction were calculated.
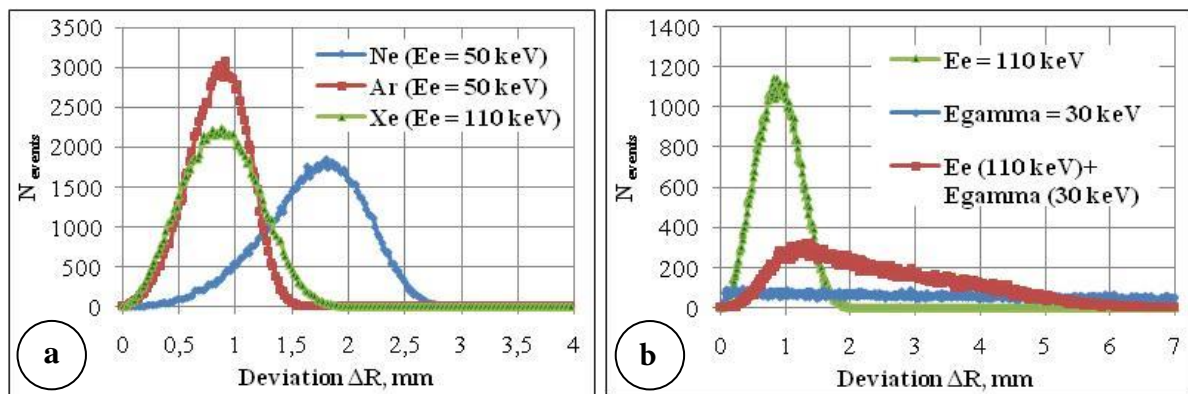

Figure 2. Distribution of deviation ΔR of determined position from the real point of interaction: a) position accuracy for Compton scattering in Ne and Ar (50 keV), for photo absorption in Xe (110 keV); b) position accuracy for photo absorption in Xe (photoelectron 110 keV, characteristic X-rays 30 keV and the total photoelectric absorption (140 keV).

For Ar-SD typical energy of secondary electron is 50 keV, while for Xe-AD – 110 keV. The simulation results are presented in the Figure 2a. Average deviation ΔR_e for Ar-SD and Xe-AD is ~ 1 mm with a mean square deviation of 0.3-0.4 mm. However, the photoelectric effect in Xe-AD is followed by a characteristic radiation with an energy of ~ 30 keV. It leads to an additional error in determination of the coordinates of the photo absorption.

The deviation of the characteristic radiation absorption from the point of X-ray emission are shown in the Figure 2b. The mean deviation of the coordinate for X-ray in Xe-AD is $\Delta R_\gamma = 8$ mm. The energy

weighted average deviation of the coordinate for "total photo absorption " is $\Delta R_{e+\gamma} = 2.4$ mm, and the FWHM of this distribution is about 3 mm.

If the detector electronics able to distinguish between single and multiple interactions, coordinate accuracy in Xe-AD can reach 1 mm.

4. Events selection in the gaseous compton camera

For identification of the initial γ-ray direction two coincident events have to be registered: Compton scattering in SD and photo absorption in AD. But there are some other combinations of physical events which cause coincidence in SD and AD. Computer simulations of the cylindrical Compton gamma camera were carried out using Gate/Geant4 framework for the development of algorithm for the proper coincidence selection. Mathematical model of the camera consists of two enclosed cylinders - Ar-SD and Xe-AD (Figure 3).
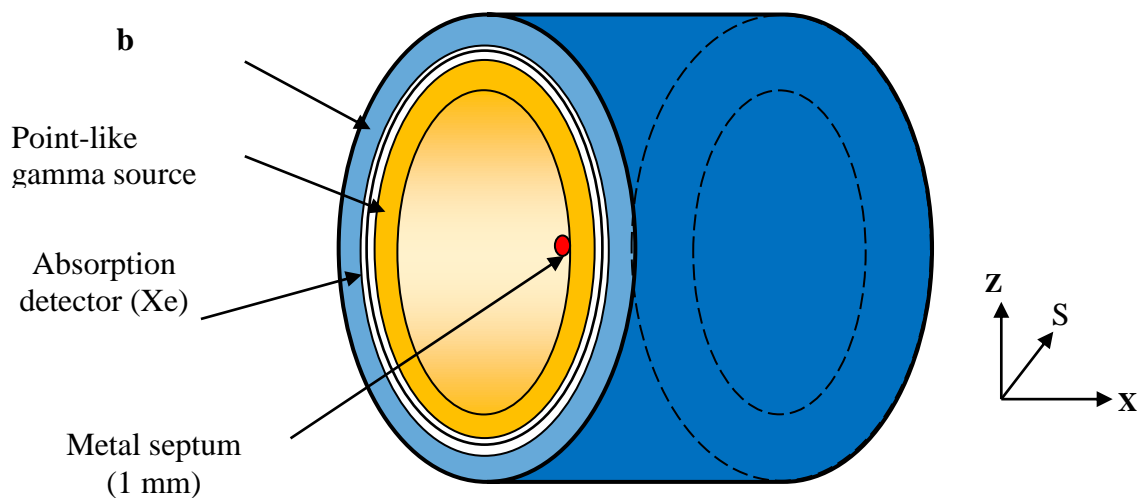

Figure 3. Model of the cylindrical Ar-Xe Compton gamma camera.

The gas pressure in both detectors is 15 bar. The inner diameter of the SD is 400 mm, outer diameter is 1100 mm. The inner diameter of the AD is 1100 mm, outer – 1700 mm. Between the detectors is a thin (1 mm) metal septum is placed. Detectors length is 500 mm. A point-like isotropic mono energetic gamma radioactive source with energy of 140 keV is placed in the center of the gamma camera. 10^6 initial γ-rays were simulated.

All the coincidences observed in Ar-Xe gamma camera were divided into eight types (see Table 1). Coincidences of the "0" type without Compton scattering occur with the photoelectric effect of the primary gamma rays in the Xe-AD and the subsequent registration of the characteristic radiation (~ 30 keV) in the Ar-SD. These coincidences do not provide any useful information and are background. Coincidences of the "1" type - "useful" coincidences, caused by Compton scattering of the primary gamma quanta in Ar-SD and following photoelectric absorption of the scattered radiation in the Xe-AD. Coincidences of the "2-7" type, resulting from the multiple Compton scattering of the primary gamma rays in the SD and the AD distort useful information.

Table 1 shows the classification of different types of coincidences and their relative contribution.

The efficiency of coincidences registration is ~ 3% when the restriction only on the total deposited energy $(E_{SD}+E_{AD}) > 100$ keV is used. The efficiency become 1% when selecting the energy as follows $1 < E_{SD} < 29$ keV, $E_{AD} > 70$ keV and $(E_{SD}+E_{AD}) > 100$ keV. Table 1 demonstrate that such selection lead to the maximal contribution of "useful" coincidences of the type "1" is (87.9%); the contribution of coincidences of the type "0" is reduced from 15.8% to 0.2%; the contribution of coincidences of the

type "4" (two Compton scatterings + Photo absorption) is practically unchanged (~ 12%).The contribution of other types does not exceed 0.5%.

It is important to take into account that about 50% of the gamma quanta emitted from the source escape through the open ends of the gamma camera without interaction.

Table 1. Classification and the contribution of the different types of coincidences («C» – Compton scattering, «Ph» – photoelectric effect)

Type	Contribution		Origin of coincidences	
	Without an energy selection in each detector	With an energy selection in each detector	1st event	2nd event
0	15,8%, (background)	0,2%, (background)	PE – photoelectron registration (110 keV) and a characteristic γ-quantum (30 keV) with different detectors (Ph)	
1	67,2%, (useful)	87,9%, (useful)	SD (one C)	AD (Ph)
2	1,5%	0%	AD (one C)	SD (Ph)
3	1,1%	0,1%	SD (one C)	AD (one C)
4	12,2%	11,5%	SD (two C) SD (one C)	AD (Ph) AD (one C+Ph)
5	0,5%	0%	AD (two C) AD (one C)	SD (Ph) SD (one C+Ph)
6	0,5%	0%	AD (one C)	SD (one C)
7	1,1%	0,3%	More than 2C	

5. Spatial Resolution of the point-like gamma sources

To estimate the spatial resolution of cylindrical Compton camera the image of two point-like gamma sources was simulated. For the image reconstruction algorithm of simple cone back projections in combination with iterative maximum likelihood estimation method (MLEM) was used [4]. Figure 4 shows a reconstructed image of two point-like gamma sources (140 keV) placed symmetrically with respect to Z axis at a distance of 80 mm from each other.

Reconstruction with a simple cone back projections method provides a spatial resolution of ~ 40 mm. A subsequent usage of the MLEM allowed to improve the spatial resolution up to ~ 20 mm. Selection of the most effective image reconstruction algorithm concerned with the design of the Compton gamma camera and largely determine its spatial resolution. It should be noted that unlike the flat Compton camera spatial resolution in the cylindrical Compton chamber is uniform throughout the field of view.
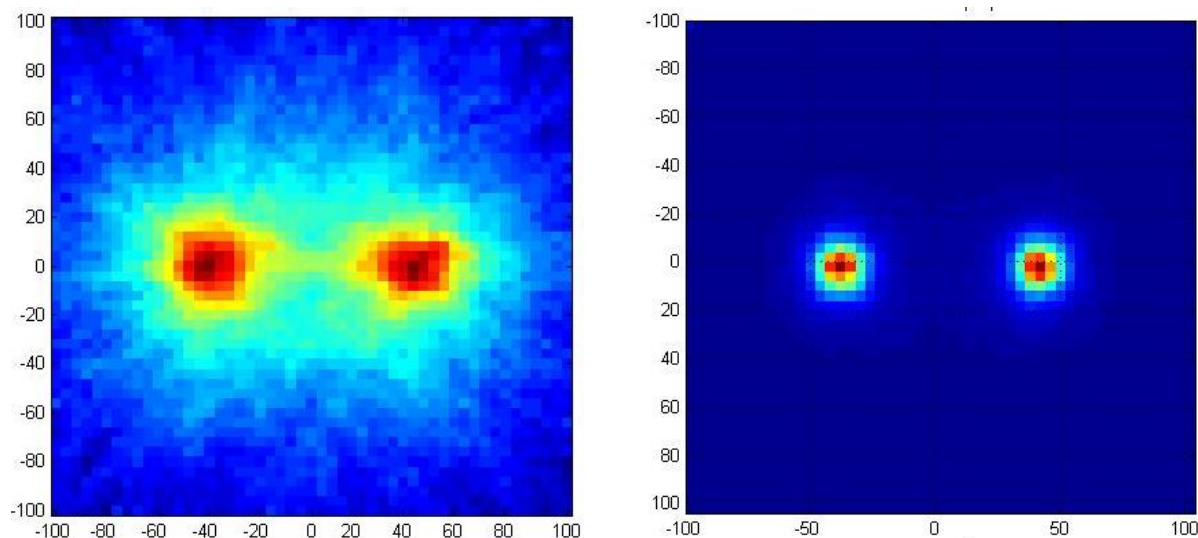
Figure 4. Reconstructed OXY plane images of two point-like isotropic gamma sources (140 keV) placed at the distance ±40 mm from Z: а) simple cone backprojection method; б) iterative maximum likelihood estimation method (after8iterations).

6. Conclusion

The following results and operating parameters of the detector were obtained via computer simulations:

- argon scatter detector with a thickness of 350 mm (at 15 bar) provides an efficiency of 140 keV gamma radiation scattering ~ 10 % and a spatial resolution ~ 1 mm;
- xenon absorption detector with a thickness of 300 mm (at 15 bar) provides an efficiency photoelectric absorption of scattered radiation~ 70 % and a spatial resolution ~ 3 mm;
- efficiency of registration of coincidences which are selected based on the energy deposit in both detectors is ~ 1 %;
- FWHM of the point-like gamma source spread function (spatial resolution) obtained with a simple backprojection reconstruction method is ~ 40 mm, and ~ 20 mm with a reconstruction based on the iterative MLEM algorithm.

Acknowledgements

References
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