Detection Optimization for Prompt Gamma Ray Imaging during Boron Neutron Capture Therapy (BNCT): A Monte Carlo simulation study

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Introduction

- Boron neutron capture therapy (BNCT)
  - ✓ Accurate radiation therapy technique based on the high cross-section of the ^{10}B(n, α)^{7} reaction
  - ✓ Thermal neutron (<1 eV) + boron → ^{7}Li ion (1.47 MeV) + alpha particle (0.84 MeV) + 478 keV prompt gamma ray
  - ✓ Occurrence point of 478 keV prompt gamma ray = Neutron capture point (boron uptake region (BUR), therapy region)
  - ✓ Detected by the single photon emission computed tomography (SPECT)
    - ► Therapy region can be monitored during the treatment using images

• Purpose

The purpose of this study was to provide the statistical analysis of detection optimization data using Monte Carlo simulation for prompt gamma ray imaging during BNCT.

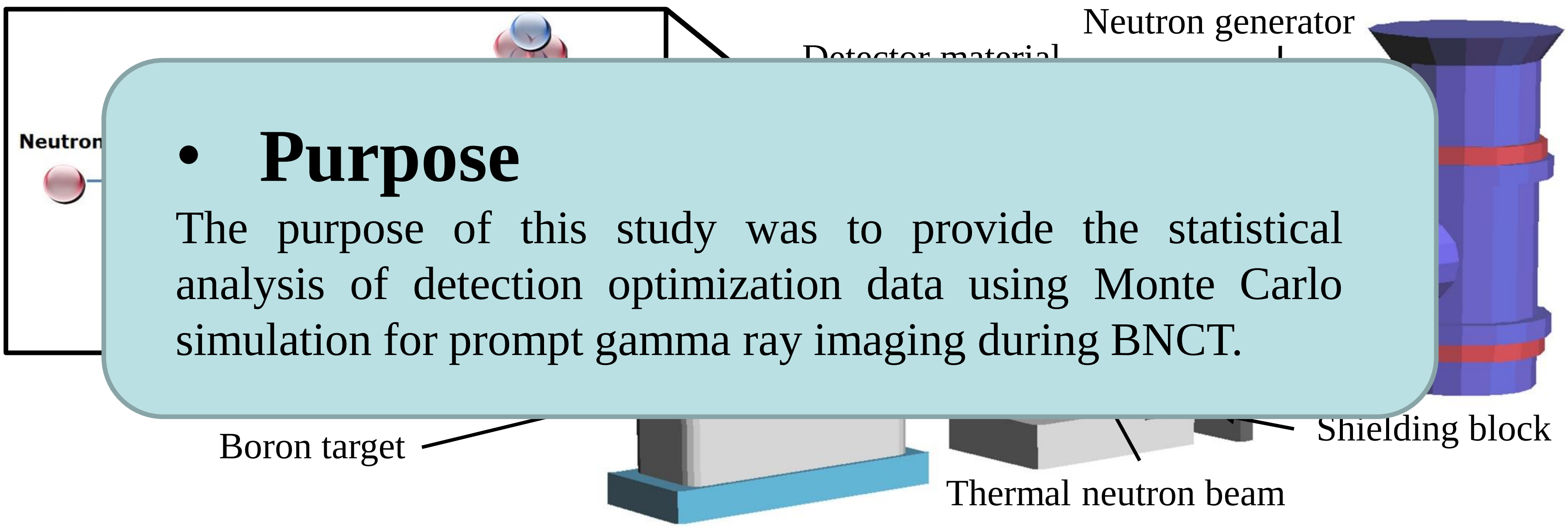

Figure 1. Diagram of simulation of boron neutron capture therapy (BNCT). The information of several detector materials was used to simulate the prompt gamma ray spectra.

Materials & Methods

- Monte Carlo n-particle (MCNPX 2.5.0)

  ✓ Materials and source simulation
    - Detector size (20 cm × 20 cm × 3 cm) → Fixed to maintain the identical physical factors excluding the materials
    - Distance between neutron source and the center of target → 50 cm
    - Distance between detector and target → 30 cm
    - Boron (density = 2.08 g/cm3) target size →
    - Source → thermal neutron (<1eV)

  ✓ Output sorting
    - Energy spectrum

  ✓ Energy resolution adaption
    - Gaussian Energy Broadening (GEB) in MCNPX
    - 511 keV, 662 keV Energy resolution of each detector
    - Full width at half maximum (FWHM)

$$\mathrm{FWHM} = a + b\sqrt{E}$$

$$\mathrm{a} = \ \mathrm{GEB\ a\ (MeV)}$$

$$\mathrm{b} = \ \mathrm{GEB\ b}\ \left(\mathrm{MeV}^{1/2}\right)$$

$$\mathrm{E} = \ \mathrm{peak\ energy\ (MeV)}$$

Materials & Methods

Table 1. Detector list and specifications (the density, the energy, and the resolution) for the Monte Carlo n-particle extended (MCNPX) simulation. Gaussian energy broadening values (GEB a, GEB b) were calculated using the Eq. (1) with the energy resolution of the 511 and 662 keV.

Detector material	Density (g/cm^3)	Energy resolution 511 keV (%)	Energy resolution 662 keV (%)	GEB a	GEB b
Bismuth Germanate Oxide (BGO)	7.13	14.20	12.50	-0.0050	0.1084
High purity Germanium (HPGe)	5.32	0.70	0.27	0.0164	-0.0180
Cadmium Zinc Telluride (CZT)	5.60	2.00	1.00	0.0360	-0.0360
Lanthanum Chloride (Cerium) ($LaCl_3$(Ce))	3.64	5.10	3.30	0.0556	-0.0413
Sodium Iodide (Thallium) (NaI(Tl))	3.67	8.60	6.50	0.0486	-0.0065
Cesium Iodide (Thallium) (CsI(Tl))	4.51	9.50	7.70	0.0286	0.0279
Cadmium Telluride (CdTe)	6.20	1.20	2.00	-0.0459	0.0728
Lutetium Yttrium Oxyorthosilicate (LYSO)	7.30	8.00	8.90	-0.0923	0.1864
Gadolinium Oxyorthosilicate (GSO)	6.70	12.00	8.90	0.0760	-0.0205
Lutetium Oxyorthosilicate (LSO)	7.40	10.00	8.40	0.0159	0.0492
Barium Fluoride (BaF_2)	4.90	11.40	8.00	0.0941	-0.0502
Yttrium Aluminum Perovskite (Cerium) (YAP(Ce))	5.40	6.70	5.70	0.0072	0.0378
Lithium Iodide (Eurodium) (LiI(Eu))	4.08	12.90	7.50	0.1814	-0.1615
Bismuth tri-iodide (BiI_3)	5.80	3.80	2.90	0.0201	-0.0010
Mercuric Iodide (HgI_2)	6.40	6.50	5.96	-0.0137	0.0657
Lanthanum Bromide (Cerium) ($LaBr_3$(Ce))	5.29	4.30	2.80	0.0460	-0.0336

Results

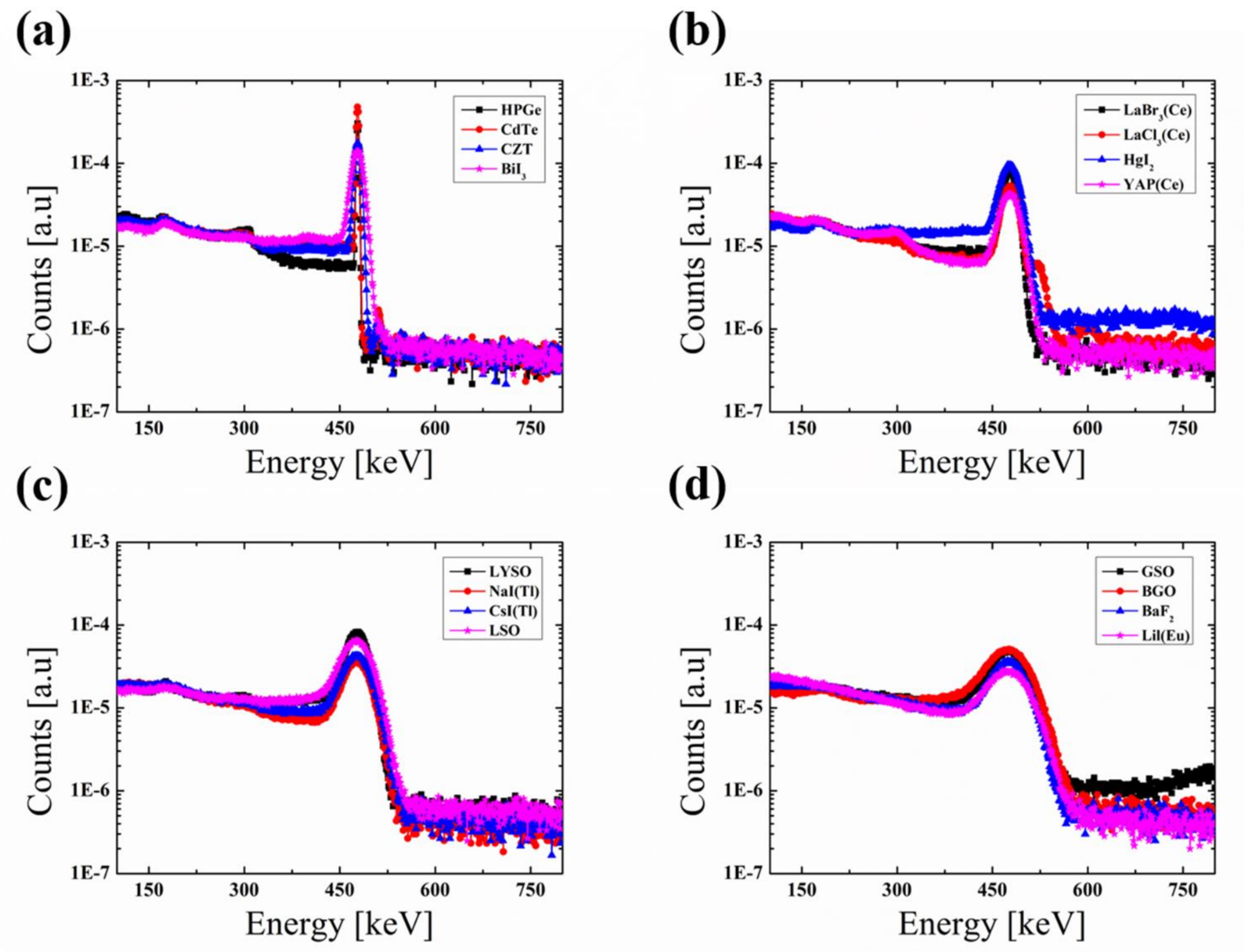

Figure 2. The Monte Carlo n-particle extended (MCNPX) simulations of the sixteen different prompt gamma ray energy spectra. Line colors depending on energy resolution level were assigned to energy spectrum of each detector in the group. (a) HPGe, CdTe, CZT and BiI_3, (b) $LaBr_3$(Ce), $LaCl_3$(Ce), HgI_2 and YAP(Ce), (c) LYSO, NaI(Tl), CsI(Tl) and LSO, (d) GSO, BGO, BaF_2 and LiI(Eu) detector materials.

Results

Table 2. Energy resolution values of the 478 keV prompt gamma ray peaks depending on the detector materials. The energy resolution is expressed as a percentage (average values by the ten iterative calculations).

Detector material	Energy resolution 478 keV (%)
Bismuth Germanate Oxide (BGO)	12.51
High purity Germanium (HPGe)	0.63
Cadmium Zinc Telluride (CZT)	2.09
Lanthanum Chloride (Cerium) ($LaCl_3$(Ce))	4.39
Sodium Iodide (Thallium) (NaI(Tl))	8.16
Cesium Iodide (Thallium) (CsI(Tl))	9.14
Cadmium Telluride (CdTe)	0.77
Lutetium Yttrium Oxyorthosilicate (LYSO)	6.74
Gadolinium Oxyorthosilicate (GSO)	11.05
Lutetium Oxyorthosilicate (LSO)	9.04
Barium Fluoride (BaF_2)	11.09
Yttrium Aluminum Perovskite (Cerium) (YAP(Ce))	5.92
Lithium Iodide (Eurodium) (LiI(Eu))	12.60
Bismuth tri-iodide (BiI_3)	3.75
Mercuric Iodide (HgI_2)	5.94
Lanthanum Bromide (Cerium) ($LaBr_3$(Ce))	4.39

Results

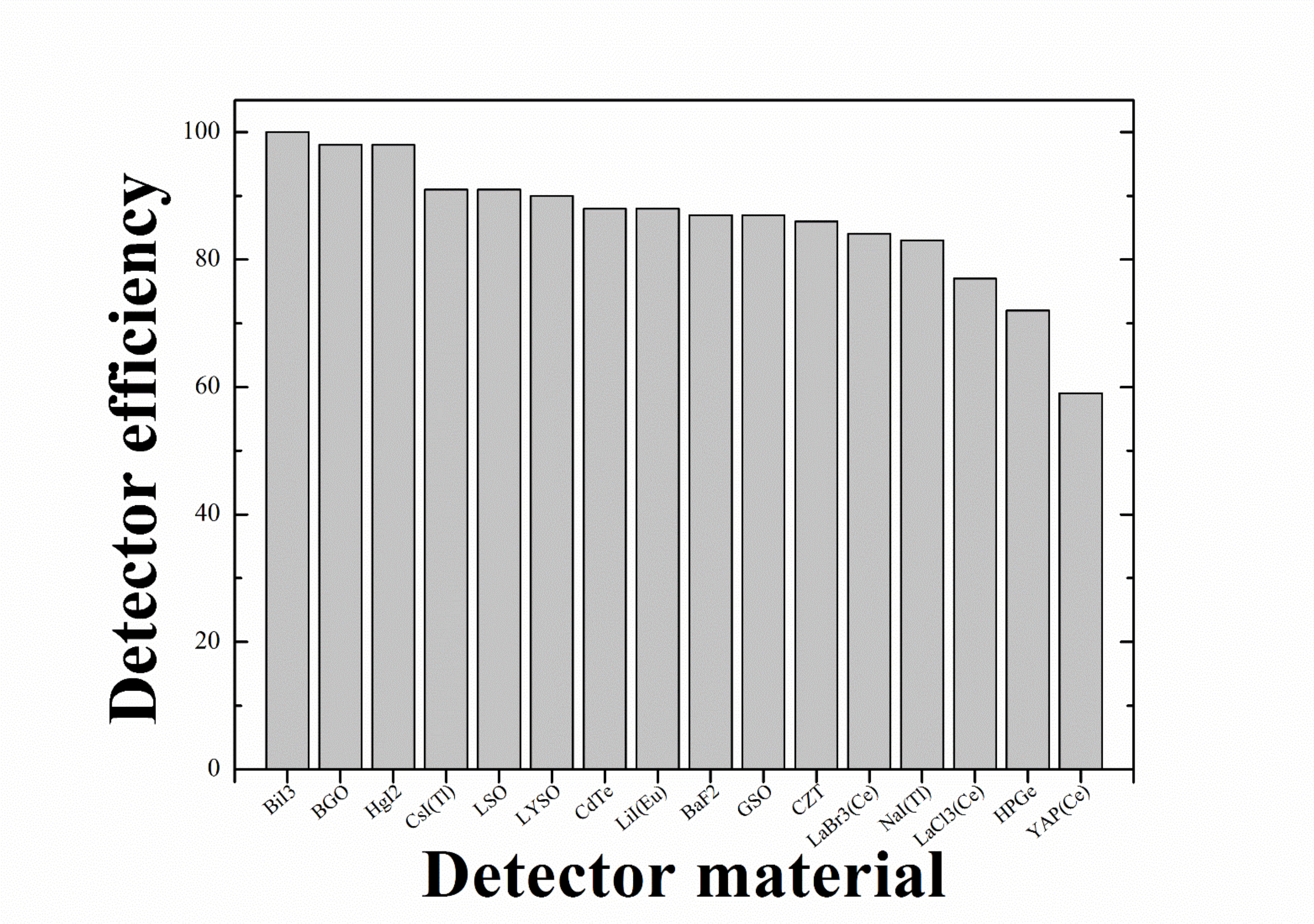

Figure 3. Detection efficiency of 478 keV prompt gamma ray according to the detector material. The standard of normalization was the detection efficiency of BiI_3. (100%)

Discussion & Conclusion

- First reported data regarding the peak discrimination of 478 keV energy prompt gamma ray → Many cases (sixteen detector materials)
- Based on the Monte Carlo method and statistical method with the identical conditions → Reliable data
- BNCT study for the peak detection within actual experiments → Our results are based

Thanks for your attention

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