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Three-dimensional cross point readout detector design for including depth information

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ABSTRACT

We designed a depth-encoding positron emission tomography (PET) detector using a cross point readout method with wavelength-shifting (WLS) fibers. To evaluate the characteristics of the novel detector module and the PET system, we used the DETECT2000 to perform optical photon transport in the crystal array. The GATE was also used. The detector module is made up of four layers of scintillator arrays, the five layers of WLS fiber arrays, and two sensor arrays. The WLS fiber arrays in each layer cross each other to transport light to each sensor array. The two sensor arrays are coupled to the forward and left sides of the WLS fiber array, respectively. The identification of three-dimensional pixels was determined using a digital positioning algorithm. All pixels were well decoded, with the system resolution ranging from 2.11 mm to 2.29 mm at full width at half maximum (FWHM).

1. Introduction

In preclinical positron emission tomography (PET), thin long scintillator crystals are used to improve spatial resolution and sensitivity [1]. Because these crystals increase the fraction of gamma rays obliquely incident on the detector surface, the spatial resolution gradually degrades from the center to the periphery of the field of view (FOV) [2–4]. This degradation is referred to as the parallax error. Spatial resolution can be improved by acquiring information regarding the depth of gamma interaction in the crystal pixels. One method for acquiring depth information is a dual-ended readout, which has been developed in many studies and has shown promising results [5–9]. However, gamma ray attenuation and scattering caused by photosensors and electronics at the front of the crystal array affect the signal-to-noise [10]. In addition, it is necessary to calibrate for depth position because of the difference between the calculated depths and the irradiation depths [11]. This calibration should be performed in all crystals.

To overcome the disadvantages of the dual-ended readout method, we designed a novel depth-encoding PET detector module. Our detector module uses a cross point readout method with wavelength-shifting (WLS) fibers [8,9,12,13] and pixel scintillation crystals. To evaluate the characteristics of the detector module, we used the DETECT2000 [14] simulation tool to perform optical photon transport in the crystal array and wavelength-shifting fibers. The PET system performance of the novel PET detector module was evaluated by GATE [15] simulations.

2. Materials and methods

2.1. Design parameters of the novel detector module

The detector module is made up of four layers of scintillator arrays, five layers of WLS fiber arrays, and the two sensor arrays. As shown in Fig. 1, the scintillator arrays and the WLS fiber arrays are arranged in alternate directions. The WLS fiber arrays in each layer cross each other to transport the light to each sensor array. The two sensor arrays are coupled to the forward and left sides of the WLS fiber array, respectively. The scintillation crystal uses LSO because of its high stopping power at annihilation gamma energy and its high light yield. The BCF91-A WLS fiber is coupled to LSO crystals [16] because the absorption wavelength range of WLS matches well with the LSO emission wavelength peak. A Hamamatsu MPPC S13360 [17] was used to measure light trapped by the WLS fibers. The MPPC measured a 3.4 mm x 3.4 mm and the active area measured 3 mm × 3 mm. The spectral response of the MPPC was 320–900 nm and the maximum quantum efficiency was 40% at 450 nm. The quantum efficiency of the WLS emission peak was approximately

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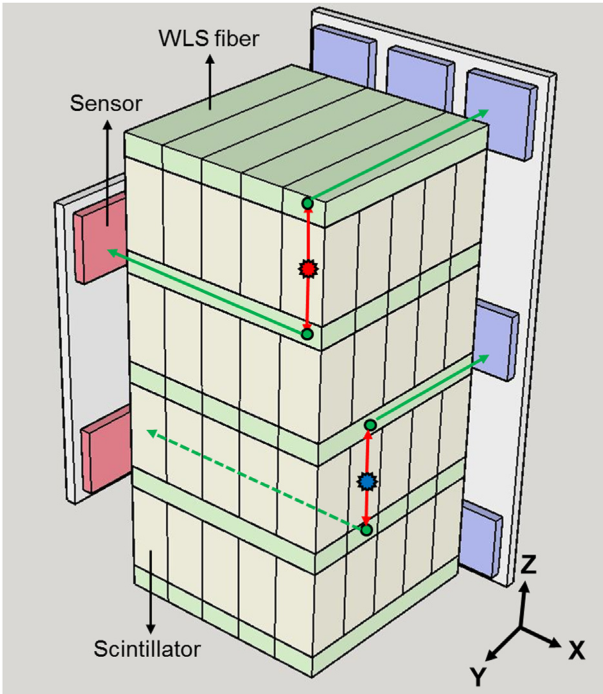

Fig. 1. Geometry of the novel detector module. The MPPC arrays are shown in blue (forward) and red (left). Light generated from the crystals (red and blue stars) is reflected in the direction of the green arrow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

37.5%. Optical grease (refractive index: 1.465) was used in the coupling material to reduce light loss caused by the different refractive indices between materials.

The LSO crystal array in each layer consisted of 5 × 5 crystals, each of which measured 2 mm × 2 mm × 5 mm. The WLS fiber in each layer was composed of 1 × 5 arrays, each of which measured 2 mm × 10 mm × 1 mm. The end of each fiber was coupled to the sensor array. The forward sensor array consisted of 3 × 3 MPPCs, whereas the left side sensor array consisted of 3 × 2 MPPCs.

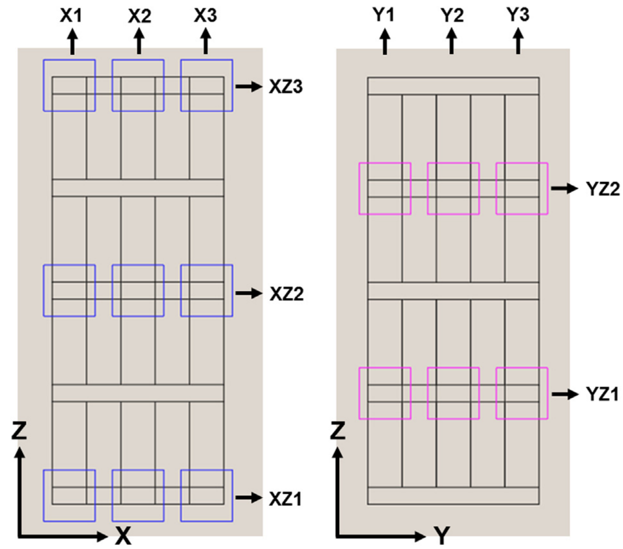

Fig. 2. Illustration of the MPPC positions and multiplexed readout for each MPPC array.

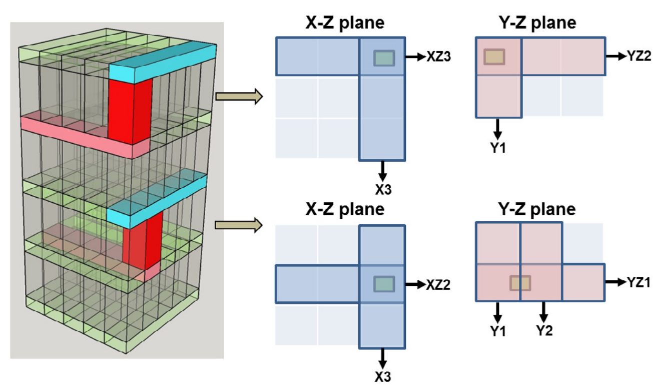

Fig. 3. Data processing of red crystals using a cross point readout method with a digital positioning algorithm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

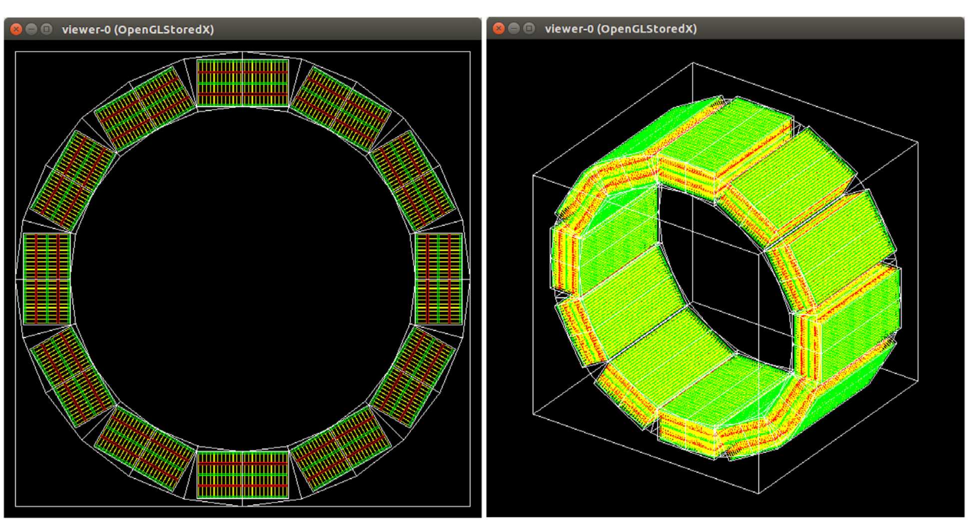

Fig. 4. Geometry of the PET system using the novel detector module.