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SemiSPECT: A Small-animal Imaging System Based on Eight CdZnTe Pixel Detectors

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Abstract

We have constructed a SPECT system for small animals that utilizes eight CdZnTe pixel detectors. The eight detectors are arranged in a single octagonal ring, where each views the object to be imaged through a single pinhole. Additional projections are obtained via rotation of the animal. Each CdZnTe detector is approximately 2 mm in thickness and is patterned on one surface into a 64×64 array of pixels with 380 micron pitch. We have designed an electronic readout system capable of collecting data from the eight detectors in listmode. In this scheme each event entry for a gamma-ray hit includes the pulse height of the pixel with the largest signal and the pulse height for each of its eight nearest neighbors. We present details of the overall design, the electronics, and system performance.

Index Terms

Biomedical imaging; cadmium zinc telluride (CdZnTe); single photon emission computed tomography (SPECT); small-animal imaging

I. Introduction

There has been rapid growth recently in demand for *in vivo* small-animal imaging capabilities. While it is possible to image small animals using suitably modified clinical imaging systems, specially designed systems can better meet the sensitivity and resolution requirements for effective small-animal imaging. The ability to produce semiconductor detectors with high intrinsic spatial resolution via photolithographic techniques means that imaging systems with a large space-bandwidth product can be made compact. By arranging multiple detectors so as to collect multiple projections simultaneously, the system sensitivity is increased while decreasing the number of rotations needed for tomographic reconstructions. We have developed a dedicated small-animal SPECT system comprised of over 3.2×10^4 resolvable detector elements that will provide high resolution and good sensitivity in a table-top device.

II. CdZnTe Hybrids

The SemiSPECT system utilizes eight of the CdZnTe hybrid detector arrays that have been developed by our group [1]. Each hybrid detector array consists of a $26.9 \text{ mm} \times 26.9 \text{ mm} \times \sim 2 \text{ mm}$ CdZnTe crystal indium-bump bonded to a custom ASIC. One side of the detector is patterned with a 64×64 array of pixel electrodes using photolithography. Each pixel is a square of $330 \text{ }\mu\text{m}$ on a side, and the pixel pitch is $380 \text{ }\mu\text{m}$. The opposite side of the detector has a planar platinum electrode to which -180 V bias is applied. The pixels are anodes in this configuration, and the “smallpixel effect” [2] allows for good photopeak fraction despite the poor hole transport in CdZnTe. The hybrid detector arrays are mounted on a daughterboard containing decoupling capacitors and transistors for buffering of the analog outputs. Connections are made to the ASIC via wire bonds.

III. Electronics

The readout ASIC provides a separate reset-gated integrator for each pixel, and the entire array is read out in a raster scan pattern at a frequency of $\sim 1 \text{ kHz}$. A schematic of the electronics for a single hybrid is shown in Figure 1. The clock signals for control of the readout cycle are provided by a Gage CompuGen CG3250 card located in the PC. The readout of all eight detectors is synchronized, with the signals from a single CG3250 being split via a clock driver board. A separate electronics board (labeled C&B Board in Fig. 1) for each hybrid carries out required level shifting of the clock signals. These boards are also used to set a number of bias voltages and currents for operation of the ASIC and contain an analog amplifier for the ASIC signal outputs. The use of separate boards for each hybrid allows for individual adjustment of these bias levels to optimize the detector performance.

We have designed a custom front-end board that uses a field-programmable gate array (FPGA) for event detection. The digitized output from each pixel has a stored baseline value

subtracted from it and the difference is multiplied by a gain value. (We initially will use only gain values of 0 and 1, providing an easy way to disable noisy pixels early in the processing chain.) The resulting value is compared to a pixel-specific threshold to determine whether a gamma-ray interaction occurred. When a pixel value exceeds its set threshold, a list-mode event entry is created that consists of a time stamp, pixel address, and the baseline-subtracted values of the hit pixel and its eight nearest neighbors. Inclusion of the nearest neighbor output is needed for accurate energy estimation and, if desired, can be used for sub-pixel position estimation or estimation of the depth of interaction [3]. Four separate SRAM modules are used to store the baseline, gain, threshold, and raw pixel values for the array. A running baseline value is computed by sampling entire pixel frames at a selected interval and computing a running average. This “on-the-fly” updating is intended to compensate for any baseline drift with time.

The back-end data acquisition electronics utilizes the same hardware as that designed for the FASTSPECT II imaging system [4]. The list-mode data stream from each front-end card is transmitted over a network-style cable to a custom PCI card located in the host computer. The incoming data is buffered in an 8MB on-board memory until the host computer is ready to download the data from the corresponding detector. Each of these back-end boards handles the data stream from two front-end boards.

IV. Mechanical Design

Each detector is attached to a copper mounting unit that contains a thermoelectric cooler. These detector units are then held in position on a copper block by a set of retaining clips. This arrangement allows for easy insertion and removal of the individual detector units to facilitate any servicing or exchange of detectors that may be required. The temperature of each hybrid is controlled by a separate feedback loop. Moderate cooling (-5°C) of the CdZnTe reduces the detector leakage current and improves performance. The copper block acts as the heat sink for the thermoelectric coolers, with a liquid chiller circulating fluid through copper tubing that surrounds the block. The apparatus is enclosed in a cylindrical, lead-lined aluminum housing. The system is designed such that a second octagonal ring of detectors can be added. Depending on the aperture used, a second ring would allow for either improved sensitivity or increased field of view.

The system is mounted with its axis vertical. Additional angular sampling for tomographic reconstruction is attained by rotating the animal using a computer-controlled rotational stage. In addition to the rotational stage, the animal holder also has a linear translation stage to facilitate loading the animal into the system and vertical positioning with respect to the imaging aperture. Figure 2 shows the main mechanical components, including the aperture, the rotational stage, the outer housing, and the copper mounting block (just visible inside the main housing). As can be seen in this photograph, the entire unit fits onto a desktop-sized optical breadboard. In the future we plan to modify the mounting scheme by turning the imaging system on its side. The animal then will be placed in a stationary horizontal position and the imaging system will rotate about the horizontal axis. The use of eight detectors in a ring configuration means that only a small amount of angular rotation of the system is needed to achieve full 360° coverage.

V. Imaging Aperture

Each detector array views the object to be imaged through a single pinhole. The imaging aperture is a cylinder made of Cerrobend (a low-melting point alloy of Bi, Pb, Sn, and Cd) with the pinholes formed in gold inserts. The current aperture has pinholes that are 0.5 mm in diameter and is configured to give a $0.44\times$ magnification of the object onto the detector arrays. This magnification is sufficient for 1 mm reconstructed tomographic resolution and will result in a system sensitivity of $\sim 5\times 10^{-5}$. A second set of pinholes of 1 mm diameter are also available. We plan to build additional aperture assemblies with smaller diameters, which will result in larger magnification, improved resolution, and higher sensitivity.

VI. First Imaging Test

As a first test of the imaging capability of SemiSPECT, a single hybrid was mounted in the apparatus and was operated using the electronics developed for imaging with a single hybrid using a parallel-hole collimator [5]. The major difference in the acquisition hardware was that a DSP-card with ADC was used for the event detection, instead of the custom front-end and back-end boards.

The phantom consisted of a 15 mm-diameter tube filled with 37 micro-hematocrit tubes (1.1 mm inner diameter). Seven of these tubes were filled with ^{99m}Tc -sulphur colloid to a height of approximately 15 mm and arranged at various spacings with respect to one another within the full group. The activity-filled tubes formed a pentagonal shape with two outward spurs. The center-to-center spacings along the points of the pentagon were between 2.5 and 2.75 mm, except for one pair separated by 4.25 mm, while the two outliers were 2.75 mm from the closest points of the pentagon. The total activity in the phantom at the start of imaging was 770 μCi . A total of 64 projection images were collected using two minute acquisition intervals. This dataset would correspond to eight rotations of the phantom for a fully-populated SemiSPECT and 16 minutes acquisition.

The image reconstruction was done using a maximum-likelihood expectation maximization (ML-EM) algorithm that utilized an analytic model for the system-response matrix. A 220 μm voxel size was used, and the reconstruction stopped at about 100 iterations. Figure 3 shows one transverse slice from the reconstructed image. A profile through the lower portion of this same reconstructed slice is shown in figure 4. The two peaks that appear in this figure represent two micro-hematocrit tubes whose center-to-center spacing was 2.6 mm, with 1.1 mm separating the activity-containing volumes. Five of the ^{99m}Tc -filled tubes are easily identified around the outer portion of the image in figure 3, while two that were also separated by 2.6 mm but located in center of the phantom are not fully resolved.

VII. Discussion

We have developed a dedicated small-animal SPECT imaging system that capitalizes on the CdZnTe hybrid detector array technology that we have previously developed in our lab. As a first demonstration of its capabilities, a phantom was imaged using a single detector and existing readout electronics. Eight detectors have been selected and are ready to be mounted in the SemiSPECT apparatus. We are currently testing the new front-end board that utilizes

an FPGA for event detection. The fully-populated system will soon be operated using the new electronics, and detailed system characterization measurements will be made. We are confident that SemiSPECT will prove to be a valuable tool for *in vivo* small-animal imaging studies.

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Fig. 1. Schematic view of the electronics for a single hybrid detector. The LAN cable connects to the back-end board in the PC.

Fig. 2.
A photograph showing the main mechanical components of the SemiSPECT imager.

Fig. 3.
A single transverse slice from the reconstructed phantom image.

Fig. 4.

A horizontal profile through the lower region of the reconstructed slice depicted in figure 3. The two ^{99m}Tc -filled tubes intersected in this profile had center-to-center spacing of 2.6 mm (reconstructed image voxels are $220\ \mu\text{m}$).