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Nuclear Instruments and Methods in Physics Research A 571 (2007) 102–105

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Preliminary studies of a simultaneous PET/MRI scanner based on the RatCAP small animal tomograph

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Available online 7 November 2006

Abstract

We are developing a scanner that will allow simultaneous acquisition of high resolution anatomical data using magnetic resonance imaging (MRI) and quantitative physiological data using positron emission tomography (PET). The approach is based on the technology used for the RatCAP conscious small animal PET tomograph which utilizes block detectors consisting of pixelated arrays of LSO crystals read out with matching arrays of avalanche photodiodes and a custom-designed ASIC. The version of this detector used for simultaneous PET/MRI imaging will be constructed out of all nonmagnetic materials and will be situated inside the MRI field. We have demonstrated that the PET detector and its electronics can be operated inside the MRI, and have obtained MRI images with various detector components located inside the MRI field. The MRI images show minimal distortion in this configuration even where some components still contain traces of certain magnetic materials. We plan to improve on the image quality in the future using completely non-magnetic components and by tuning the MRI pulse sequences. The combined result will be a highly compact, low mass PET scanner that can operate inside an MRI magnet without distorting the MRI image, and can be retrofitted into existing MRI instruments.

PACS: 87.57.−s

Keywords: PET; PET/MRI; Simultaneous PET/MRI; RatCAP

1. Introduction

The ability to acquire high resolution anatomical data as well as in vivo quantitative functional information is becoming an increasingly important factor in the diagnosis of disease. The recent onset of the use of dual modality PET/CT imaging to provide this type of information has had a profound effect on clinical diagnosis in radiology, oncology and other areas of nuclear medicine, and has been reflected by the vast increase in the number of commercial PET/CT scanners on the market today. However, while positron emission tomography (PET) can provide high sensitivity and high specificity functional information, CT exhibits poor soft-tissue contrast, and also subjects the patient to a significant additional radiation dose over and above the dose received from PET. On the other hand, magnetic resonance imaging (MRI) provides excellent soft-tissue contrast and anatomical detail, and does not subject the patient to any additional radiation dose. Moreover, the ability to acquire both data sets simultaneously would provide perfect co-registration of the two images.

We have undertaken the design of a simultaneous PET/MRI scanner based on the technology used for the RatCAP small animal tomograph that is compatible with the high magnetic fields and RF pulses that are present in an MRI scanner [1]. The detector will be constructed out of

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0168-9002/$ - see front matter
doi:10.1016/j.nima.2006.10.039

all nonmagnetic components so as not perturb the MRI image, and will be well shielded in order to minimize the effect of the MRI RF pulses on the PET readout electronics, and also prevent the PET readout signals from interfering with the NMR signals detected by the MRI. This paper will describe the overall system design and will present some of the first MRI images obtained with various components of the system inside the field of the MRI.

2. Technical approach

One of the main problems faced in combining PET and MRI into a single scanner is that conventional PET tomographs use photomultiplier tubes that cannot operate in the vicinity of the high magnetic fields. There have been a number of efforts to develop a combined PET/MRI scanner that have used different approaches to solve this problem. One of the first [3,4] utilized long optical fibers to bring the light from scintillating crystals outside the magnetic field to a region where the phototubes could operate. However, while this design did lead to some useful biological studies [5,6], it suffered from low efficiency and light loss in the fibers, resulting in poor sensitivity and signal to noise performance. In addition, the large number of fibers could not be easily implemented in a full scale system.

A more recent approach has been to utilize avalanche photodiodes as photodetectors which can work inside the magnetic field of the MRI. Several groups have explored this possibility and the initial results look very encouraging [7–9]. Our approach that is based on the RatCAP design also uses APDs, and incorporates them into an integrated, compact arrangement using arrays of LSO crystals and highly integrated electronics.

The RatCAP is a small but complete 3D tomograph that is designed to image the brain of an awake rat [2]. Fig. 1 shows the complete tomograph prior to installation into its external housing. It consists of a 4 cm diameter ring containing 12 block detectors, each of which consists of a 4×8 array of $2.3 \times 2.3 \times 5\,mm^3$ LSO crystals read out with a matching array of avalanche photodiodes (Hamamatsu S8550). The APDs are read out with a custom-designed ASIC implemented in 0.18 μm CMOS technology for its small size, high level of integration and low power. This ASIC produces a 32:1 multiplexing of the LSO/APD pixel arrays and delivers a purely digital signal to readout module that adds a time stamp with resolution of ~1.3 ns. The data is then sent in list mode to a separate receiver board, which, in the present design, is based on VME architecture. However, this part of the readout system has recently been redesigned and is being implemented using an optical G-link and PCI based data acquisition system which will allow placement of these readout components well outside the magnetic field.

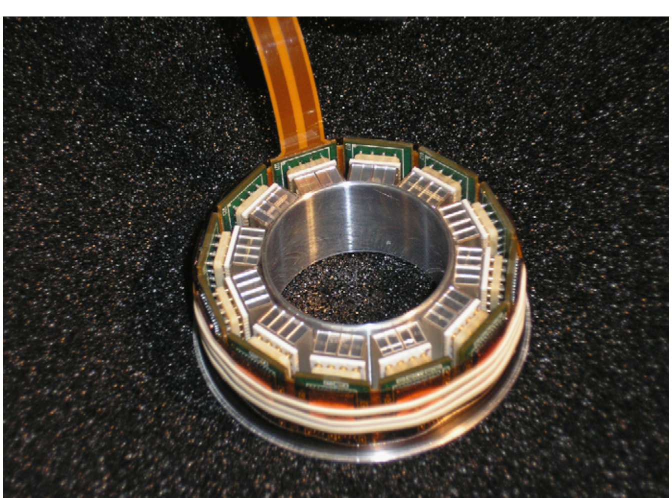

Fig. 1. The RatCAP tomograph consisting of 12 LSO arrays with APDs and associated readout electronics.

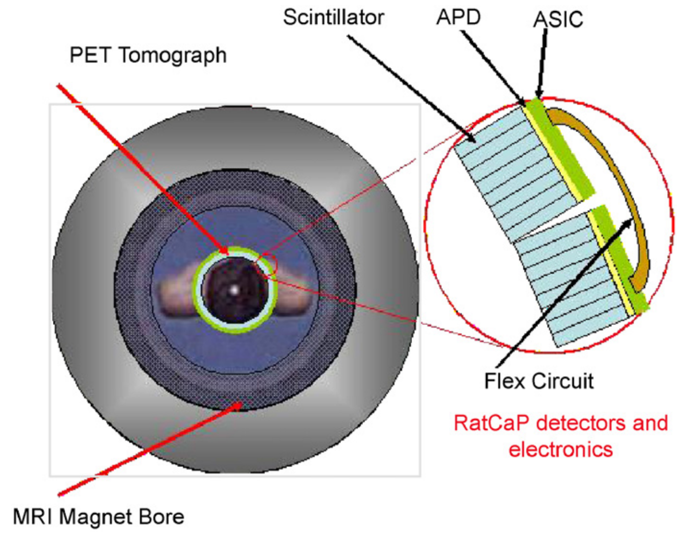

Fig. 2. Simultaneous PET/MRI scanner based on the RatCAP detector modules and readout electronics.

The overall design of the proposed simultaneous PET/MRI scanner is shown in Fig. 2. The RatCAP detector modules would be located around the outside of the RF pickup coil of the MRI. These modules consist of the LSO crystals, the APD arrays, the readout chips and the flexible readout circuit. The LSO arrays could be made thicker (~20 mm) than the 5 mm arrays that are currently used in the RatCAP, which would increase sensitivity. The entire assembly would fit within a radial distance of ~3–4 cm outside the RF coil, and would have a relatively small number of cables coming out of the bore of the MRI. In addition, the power consumption of the ASIC is only ~125 mW/chip, which would help limit the amount of heat generated inside the bore.

3. Preliminary results

A nonmagnetic version of the RatCAP has now been constructed that minimizes the amount of magnetic material inside the MRI field. It includes a special version of the Hamamatsu S8550 APD arrays with nonmagnetic pins, nonmagnetic sockets for the APDs, and a nonmagnetic flexible circuit board and cable for the readout.

We have tested many of the RatCAP components inside the 4 T MRI scanner at Brookhaven in order to study their effect on the MRI image. We also designed a special RF pickup coil consisting of two Helmholtz coils oriented in two perpendicular directions that fit inside the RatCAP and allow compensation for any residual magnetic effects or eddy currents. While we have not yet tested the complete RatCAP detector inside the field, we found that we can compensate for each of the RatCAP components separately using this coil, and that the resulting MRI images are essentially free of distortion. Fig. 3 shows an image of a live rat brain obtained with the aluminum housing for the RatCAP, and the image is virtually free of any artifacts or distortion. We believe this housing would cause the largest effect on the image of any of the RatCAP components due to possible eddy currents. Based on this, we feel confident that the complete detector will also allow for high-quality, distortion-free images to be obtained.

Fig. 3. MRI image obtained with the aluminum housing of the RatCAP detector inside the BNL 4 T MRI scanner.

The RatCAP chip was tested inside the MRI scanner and was found to be unaffected by the magnetic field. Fig. 4 shows pulse height distributions obtained with an LSO and APD array using a ^{137}Cs source read out with the RatCAP readout chip inside the field compared with the pulse height distribution obtained outside the field. The spectra show virtually no change as a result of the field. The data from inside the scanner were obtained with no gating, although some form of gating could be applied in order to avoid the noise picked up by the RatCAP during the application of the RF pulses.

We have also tested that MRI RF pulses do not affect the digital readout of the RatCAP chip. This readout uses a 100 MHz clock that could in principle get out of phase when the RF is applied. The detector was shielded inside its aluminum housing, and the time stamp module and readout cables were shielded with copper foil for the test, although not as completely as could be done in a final design. We confirmed that the readout clock was not disrupted by the RF and that the readout can operate continuously during the RF pulse sequence. However, we may still choose to gate the readout off during the actual time of the RF pulse in order to avoid possible noise pickup in the readout.

We also measured the level at which the 100 MHz clock signal was detected by the MRI pickup coil. As shown in Fig. 5, although the amount of pickup was substantial at 100 MHz, it was extremely small at the 170 MHz operating frequency used by the 4 T MRI scanner. This may require a change in the clock frequency for other scanners using different frequencies, although we believe that this pickup can be further reduced by improved shielding of the detector and cables.

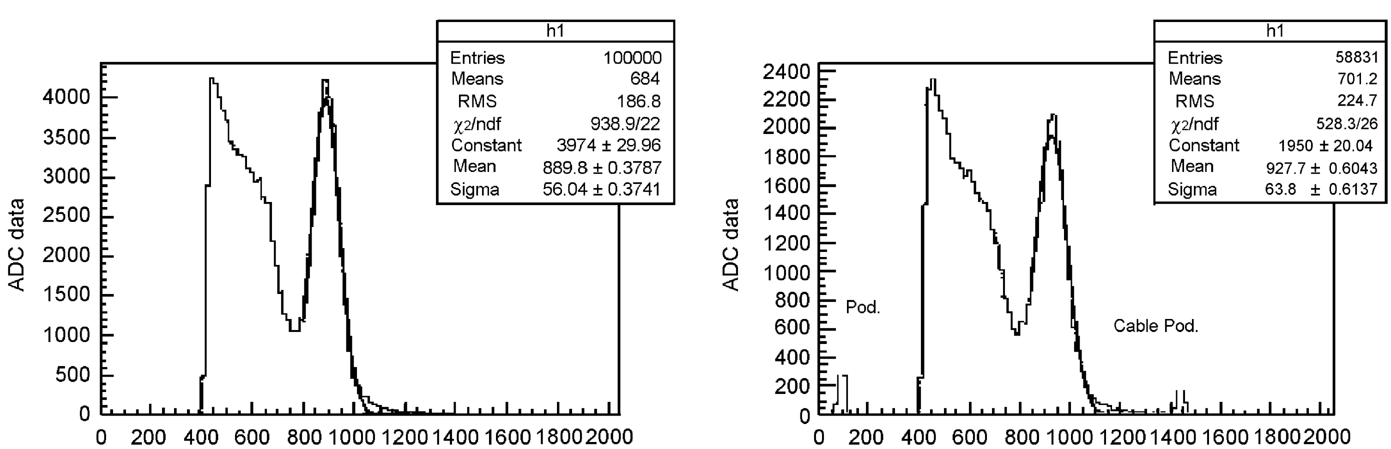

Fig. 4. Comparison of ^{137}Cs gamma ray spectra taken with the RatCAP chip inside and outside the 4 T magnetic field of the MRI.

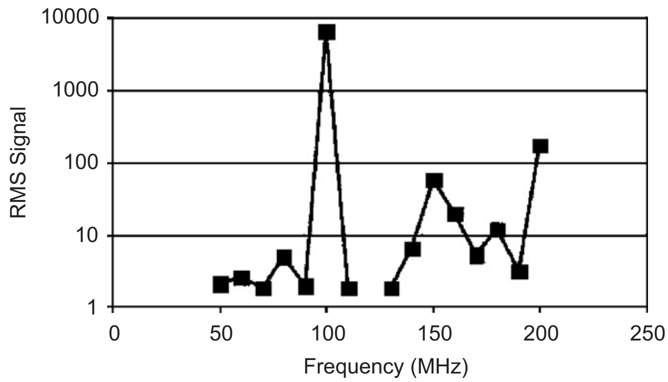

Fig. 5. Relative signal strength measured with the RF pickup coil with the RatCAP readout clock running inside the bore of the MRI. The operating frequency of the BNL 4 T MRI scanner is 170 MHz.

4. Summary

In summary, we have studied many of the critical components of the RatCAP design and shown them to be compatible with operation inside the magnetic field of the MRI. High quality MRI images have been obtained with all of the major RatCAP components inside the field, and we have shown that the RatCAP detector and its various readout components work inside the field, even in the presence of strong RF pulses. We feel that this design can lead to a practical simultaneous PET/MRI scanner, which would be a major advance in terms of clinical and diagnostic dual modality imaging. We soon plan to test a fully functional RatCAP system inside the 4 T MRI and another 9.4 T system, and hope to obtain the first simultaneous PET/MRI images.

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