An Overview of the Clear-PEM Breast Imaging Scanner

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Topic: International research groups specifically working on improving gamma ray, positron emission and x-ray transmission cameras dedicated to breast cancer imaging, and clinical imaging results

Abstract: We present an overview of the Clear-PEM breast imaging scanner. Clear-PEM is a unique dual-head Positron Emission Mammography scanner using APD-based detector modules that are capable of measuring depth-of-interaction (DOI) with a resolution of 2 mm in LYSO:Ce crystals. Such capability leads to an image spatial resolution of 1.2 mm and a high efficiency, foreseeing the detection of 3 mm breast lesions in less than 7 minutes exams. The full system comprises 192 detector modules in a total of 6144 LYSO:Ce crystals and 384 32-pixel APD arrays readout by ASICs with 192 input channels that represents an unprecedented level of integration in PET systems. Throughout the project and besides the detector module, we had developed dedicated Frontend and Data Acquisition electronics, the mechanical design and construction of the detector heads and the robotic gantry, as well as all the software that include calibration (energy, time and DOI), normalization and image reconstruction algorithms. In this work we will discuss the developments and present the commissioning results of the detector before the beginning of the clinical trials program, scheduled for the end of the present year.

1. Clear-PEM Concept and Development

We have developed a dual-head Positron Emission Tomography scanner dedicated to breast cancer imaging [1]. The scanner called Clear-PEM, because of the collaboration with Crystal Clear-CERN, uses APD-based detector modules in a double-readout scheme for DOI measurement in LYSO:Ce crystals - Fig. 1a. The DOI coordinate is determined from the asymmetry of the light collected on the two APD pixels reading out the same crystal. The detector module performance allows to measure the photon interaction coordinate along 20 mm LYSO:Ce pixels with a resolution of 2 mm (FWHM) [2]. That reduces the degradation of the spatial resolution due to the parallax effect, in particular when the scanner operates at smaller separation distance between the detectors (8-10 cm) in order to increase the photon detection acceptance. We had investigated the influence of DOI resolution on reconstructed images using simulated data and had concluded that a 2 mm DOI resolution allows to achieve an image spatial resolution of about 1.2 mm [3]. Such result was later confirmed by measuring the spatial resolution of a $^{22}$Na source reconstructed image using our technology - Fig. 1b.

Fig. 1 (a) Drawing of the developed detector module for DOI measure. (b) A reconstructed image of a $^{22}$Na source with 1 mm diameter using the Clear-PEM technology. The image was reconstructed using the OSEM-3D / STIR algorithm that we have adapted to planar geometries.
Such result illustrates the success of the detector module concept. The detector module design allows to achieve not only a high spatial resolution but also a high detection efficiency. It consists on a matrix of 32 LYSO:Ce crystals with 2x2x20 mm$^3$ coupled on both ends to APD arrays that can be assembled in a planar arrangement within the detector heads that provides a more uniform angular coverage. Such planar geometry is also rather flexible and can easily accommodate different breast sizes by simply positioning the detector heads at different separation distance and rotation angles. For that purpose, we developed a supermodule structure that groups 12 detector modules placed between a top and a bottom Frontend board - Fig. 2a. Each Clear-PEM detector head has 8 of these supermodules covering 15x17 cm$^2$. We developed a Frontend board that interfaces directly with the APD arrays, each one equipped with two 192 channels low-noise ASICs to process the APD output signals, able to readout 768 electronic channels in a high compact area of 12x4.5 cm$^2$ [4]. We consider the Clear-PEM Frontend electronics one of the most innovative systems currently available for APD-based PET detectors, representing a significant contribution for the development of highly compact PET scanners.

In Fig. 2a we present a photograph of the Clear-PEM scanner showing the robotic gantry, the detector heads and the examination table for the patient to lie prone. The robot controls the rotation and the separation distance between the detector heads. We also show the assembled supermodules - Fig 2b - and a picture of the detector heads without the external housing mounted on the gantry and operating with the Data Acquisition System [5] - Fig. 2c.

2. Performance Results

We currently have all the 16 supermodules needed for the two detector heads, the Frontend and Data Acquisition systems fully working and we are now performing the detector energy, time and DOI calibrations. A preliminary analysis of the data already taken allows us to presently conclude that all the initial and challenging requirements of the Clear-PEM project were achieved. Besides the DOI resolution
of 2 mm already mentioned, we determine the energy and time resolutions. An energy resolution of 15.3% at 511 keV is achieved for a mean APD gain of 100 and a good energy linearity of the crystal-APD-ASIC-ADC readout chain is observed in all supermodules. We also measure a single photon time resolution of 1.3 ns r.m.s at 511 keV leading to a 4 ns FWHM time resolution for photons in coincidence. The measured r.m.s. noise of an equivalent energy of 7 keV (1200 e⁻ ENC), using the full data readout chain and the APD voltage biasing system, allows us to operate the detector with an energy threshold down to 50 keV. That result fully supports one of the design goals for the detector which is the increase of detection efficiency by reading out photon events that undergo in-detector Compton scatter, in opposition to pixelized PET detectors that only process photoelectric events. In summary, these results prove that our research group has successfully accomplished an unprecedented level of integration of a large number of APD channels (12288) for a human PET scanner, overcoming all the technological challenges that it represents.

Throughout the project we have also developed novel methods for the detector calibration based on both the use of external sources and the natural background radiation of the LYSO:Ce crystals as well as specific normalization and reconstruction algorithms in order to improve the quality of the images for planar PET scanners. Such methods incorporate and take advantages of the DOI capability of the detector and we have successfully tested them for extended and point sources [6]. We used simulations to investigate the lesion detectability with our scanner for a 7 minute exam [3]. The results lead us to conclude that we will be able to detect very small breast lesions, down to 3 mm, in a few minutes exam – Fig. 3.

3. Next Steps

We are now preparing to transfer the full Clear-PEM system to the department of Nuclear Medicine of the Hospital that will conduct the clinical trials. Until then, we will continue to work on the detector commissioning and characterization of the image quality. The results and conclusions arising from this systematic work will be presented for the first time at this workshop. We feel that presenting the Clear-PEM project, the technological innovations developed for this PET detector and sharing our experiences in many essential aspects like the design of high-resolution PET detector modules, state-of-the-art electronics and software applications, associated with the encouraging results already achieved, are of great interest to the Medical Physics community attending the workshop. Our research group is currently developing, in the context of the CERIMED activities (ClearPEM-Sonic project), multimodal PET and US breast imaging. The benefits of PET/US compared with PET alone for mammography have been evaluated and we are now building a next version of the Clear-PEM scanner that incorporates an enhanced US probe as an essential tool for the further improvement of breast cancer detection and diagnosis. Finally, the observed low-noise performance of the Clear-PEM technology has encouraged on-going investigation of its possible application to a multimodal SPECT-PET scanner.
References:


