Report for Exchange Program at UCL

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1 Introduction

Traditional X-ray radiotherapy is increasingly being sidelined by high-energy charged particle irradiation techniques, for the treatment of various types of tumours. These new techniques result in a precise high-dose delivery to the tumour area, reducing the risk to surrounding healthy tissues. Neutrons allow a highly selective therapeutic modality when used in neutron capture therapy (NCT), providing additional advantages due to their higher relative biological effectiveness (RBE). The working principle of NCT is to exploit the high thermal neutron cross-section of specific nuclides, loaded in the target to damage the tumour volume. Boron Neutron Capture Therapy (BNCT) arises from these considerations. A radiopharmaceutical containing ^{10}B is conveyed to the tumour area and irradiated with thermal (or epithermal) neutrons. The capture reaction of ^{10}B with thermal neutrons produces high Linear Energy Transfer (LET) particles, which deposit the total therapeutic dose at cellular level, and γ-rays emitted at particular energies that exit the patient's body. Since these γ-rays are emitted in situ, and their emission rate is proportional to the neutron capture reaction rate. Their detection allows real-time monitoring and quantifying of the delivered radiation dose and its distribution during the therapy. For this purpose, dedicated tomographic imaging systems based on SPECT (Single Photon Emission Computed Tomography) have been proposed, but never made. In recent years, Boron Neutron Capture Therapy (BNCT) has experienced a significant surge in popularity, largely attributed to remarkable innovations within the particle accelerator field. This evolution has made BNCT more accessible and practical for clinical applications. Unlike the past, when neutrons were primarily available only within nuclear reactors, the contemporary breakthroughs in accelerator technology have enabled hospitals to integrate neutron sources directly within their facilities.

2 My Work

My work aimed to adapt a gamma module already developed to use it like an imager, so designing a collimator and a neural network for position reconstruction. We proposed a detection system, called BeNEdiCTE, based on a squared $LaBr_3$(Ce+Sr) scintillator crystal, with dimensions of $5\,cm \times 5\,cm \times 2\,cm$, optically coupled to a matrix of 8×8 NUV-HD SiPMs from FBK (Trento, Italy), read out by 4 16-channel GAMMA ASICs. The collimator proposed is a channel-edge pinhole designed starting from a knife-edge with 1 mm aperture size. The edges were then cut by 2 mm to reduce the scattering of gamma rays, resulting in an overall channel aperture of 5 mm. The final configuration has been designed to feature a field of view (FOV) of 5 cm for both the detection module and the target, reaching values of spatial resolution about 8 mm and geometric efficiency of 3.84×10^{-6}, evaluated for gamma rays at 478 keV. An artificial neural network (ANN) has been developed to reconstruct the position of interaction of gamma particles during the acquisitions. The model architecture is a fully connected regression ANN, comprising 64 input neurons, two hidden layers with 25 neurons each, and 2 output neurons for the x- and y-coordinate predictions, respectively. The network achieves 2.5 mm resolution in the crystal region, slightly worsening towards the edges. The neural network's performance was tested in a controlled experimental setting at the Laboratory of Applied Nuclear Energy (LENA) facility located in Pavia, Italy. At LENA, we conducted a series of experiments involving the irradiation of a vial containing boron powder with a neutron flux, at different concentrations and at different positions. Given the encouraging results of 2D image reconstruction with our system, the research was poised to advance into the tomographic imaging field.

3 Improvements at UCL

3.1 Summary

The purpose of the exchange programme was to establish viable conditions for performing tomographic measurements for Boron Neutron Capture Therapy (BNCT). The key objectives included:

- **Implementing the Channel Edge Feature for Pinhole Collimator:**
  The first task was to incorporate the channel edge feature for the pinhole collimator into the STIR (Software for Tomographic Image Reconstruction) framework, as this feature had not previously been implemented in STIR.

- **Designing a BNCT SPECT System:**
  The next objective was to design a BNCT single photon emission computed tomography (SPECT) system. This design aimed to address the specific imaging requirements of BNCT and to create a system that could potentially be integrated with CT scanners. Such integration would enable multimodal imaging, combining the functional imaging capabilities of SPECT with the anatomical detail of CT.

3.2 Channel Edge Feature

The implementation of channel edge pinhole imaging in STIR involves significant modifications to the collimator parameter file, allowing users to select their preferred pinhole model and specify the channel depth. The code uses a geometric approach to evaluate the projection of each image voxel through the pinhole channel onto the detection plane. This process accurately determines the intersection points of the voxel projection paths with the pinhole surface and subsequently with the detector plane. The projections through the pinhole channel are convolved with the intrinsic PSF of the detector. This convolution produces the system weight matrix, which characterises the sensitivity of the imaging system over different voxel positions and intensities. Furthermore, the integration of this channel edge pinhole code with existing functionalities in STIR, such as depth of interaction (DOI) correction and additional PSF corrections, remains the same. This integration preserves the functionality and performance of these existing modules without requiring any modifications. The code was then validated using simulated data generated by the ANTS2 software. The validation involved simulating projections of a cylindrical radiation source using our imaging system, which includes the detector and the channel edge collimator. These simulated projections were then compared with the forward projections of a ROI cylinder of the same dimensions. This validation verified the correspondence between the simulated projections of the cylindrical source and the forward projections of the ideal ROI cylinder. This process confirmed that our implemented code effectively models the behaviour of the imaging system, taking into account factors such as pinhole geometry, detector characteristics and PSF effects. The newly implemented code was then used to design a tomographic setup for experimental measurements at the LENA facility in Pavia, Italy. Prior testing and validation demonstrated that STIR is capable of reconstructing tomographic images of a boron source even in scenarios with limited angular projections, specifically from 0 to 180 degrees of rotation. This capability is critical for practical applications where full angular coverage may be limited due to experimental or operational constraints.

3.3 Design of a BNCT SPECT-CT System

The combination of SPECT (single photon emission computed tomography) and CT (computed tomography) offers several advantages, including reduced acquisition time, improved attenuation correction and enhanced fusion of anatomical and functional images. These benefits are particularly important in medical imaging applications where precise localisation and characterisation of abnormalities are critical. Simulations of the Nagoya BNCT (Boron Neutron Capture Therapy) facility have led to re-evaluating the collimator structure to serve the dual purpose of optimising imaging performance and shielding against large background radiation. It has been analytically demonstrated that the combination of two SPECT heads, each made up of 5 BeNEdiCTE modules, and the newly designed collimator, allows a good SNR to be obtained with only 6 rotations at an angle of 30°, saving costs and leaving enough space for the integration of a CT scanner.

4 Outcomes and Future Work

Part of this work has been accepted for an oral presentation at the 2024 IEEE NSS MIC RTSD conference. We intend to replicate the tomographic measurement setup that is been simulated at the LENA facility. The success of these measurements, with comparisons to our simulations, will result in a publication. According to the SPECT-CT systems for BNCT, our future work will comprise a quantitative evaluation of the process of speeding up the reconstruction of the newly designed system with STIR and the use of CT attenuation maps.