

The Personalized Remote Radiation Tracking Portable Organ Dosimetry Device

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Abstract— We are developing a Personalized Remote Radiation Tracking Portable Organ Dosimetry Device (PRRT PODD) for at-home monitoring of patients receiving radiopharmaceutical therapy. The goal of this work is to provide a user and facility friendly device to enable organ at risk (OAR, i.e., kidneys) dosimetry for patients undergoing Lu-177 DOTATATE treatment. The PRRT PODD consists of a portable frame with wings that encircle the patient's torso from the base of their kidneys to the top of their liver. In addition, there is a registration pad that enables precise positioning of the patient in the PODD for daily measurements. The patient lies down in a PODD template during their therapy qualifying PET/CT scan. This registers the PODD to their anatomy. Using software tools, a sensitivity matrix between the patient's OAR and tumors is determined for a two-dimensional (2D) array of potential detector locations on the PODD. Using this matrix, 16-32 detector locations are selected based upon the patient's specific anatomy to enable activity estimation for the patient's OAR. After one in clinic measurement to normalize with a standard of care SPECT/CT scan taken at 24-hours after therapy administration. The PODD will be sent home with the patient for fourteen 5-minute daily measurements. An overview of the PODD development along with results from simulations based on human imaging examples will be provided at the workshop.

Index Terms— Theranostics, portable, personalized, remote radiation monitoring, wireless.

I. INTRODUCTION

THE overall aim of this project is to develop portable, low-cost, patient friendly technology to enable personalization of Lu-177 DOTATATE radiopharmaceutical therapy for neuroendocrine tumor (NET) patients. Currently in the US and in many parts of the world, patients receive a standardized treatment protocol, with no requirements for determining dose to their organs at risk (OAR). Without any dose monitoring, standardized treatments must be conservative in nature and therefore most patients are under treated. If dose to OAR is determined for each treatment cycle, patients can receive personalized therapies that most medical professionals believe will improve treatment outcomes. We are developing the Personalized Remote Radiation Tracking Portable Organ Dosimetry Device (PRRT PODD) to enable at-home monitoring of the radiation washout from a patient's OAR and tumors as they receive Lu-177 DOTATATE therapy. At-home measurements along with a quantitative SPECT/CT scan collected 4 to 24-hours post treatment can be used to estimate dose to a patient's OAR and tumors. This project's overall goal is to demonstrate that the PRRT PODD can be a cost-effective and patient friendly technology to facilitate Lu-177 treatment optimization/personalization based upon measured dose to a

patient's OAR. We provide an overview of technology we have developed to enable at-home usage of the PRRT PODD.

II. METHODS

The PRRT PODD

The PRRT PODD (Figure 1) is constructed of a baseplate and two wings that wrap around the patient. All components and hardware are nominally non-metallic (carbon-fiber, Teflon, PLA, balsa wood, and polymer adhesives). The wings are made of 3D printed slats that interconnect. Joints between slat can articulate or be locked into position. In this way, the wings can be custom fit to a patient prior to a staging scan and then locked into two rigid half-shells. In their locked configuration, the wings can still pivot at their baseplate hinge, allowing a patient to enter or exit the PODD; latches and alignment cones are used to secure the half-shells in their dosimetry configuration.

We use a modified NEMA NU2-2018 (IQ) phantom to measure positioning repeatability. Silicon pads are adhered to the back of IQ phantom to simulate shoulder blades that would imprint upon an oncology-style vacuumed alignment cushion. This cushion is itself aligned to the carbon-fiber baseplate by vacuum-forming it onto baseplate registration features. The IQ background chamber is empty (air filled) and the spheres are water filled for use as alignment targets.

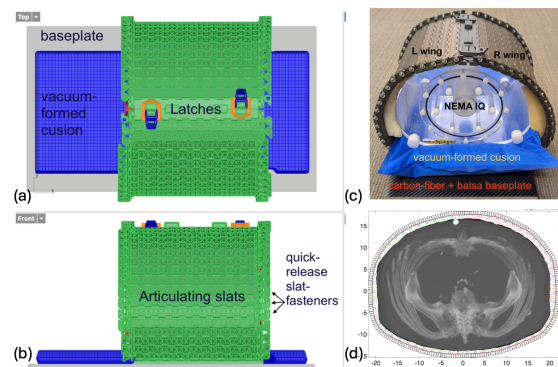


Figure 1. (a,b) top and side view of PODD. Vacuumed formed registration pad and articulating wings are shown. (c) Photograph of actual PODD with NEMA IQ phantom. (d) Illustration of potential detector positions around human subject (human image is maximum intensity pixel of CT image of torso of patient).

PODD Electronics

The data acquisition system employs a modular three-board architecture that separates digital processing, analog front-end, and system control functions onto dedicated printed circuit boards (PCBs). The PODD electronics are organized as a vertically stacked assembly of three interconnected PCBs,

referred to as the “three-board sandwich.” This architecture physically separates distinct functional domains while maintaining a compact form factor through board-to board header connections. Figure 2 shows the assembled stack with each layer labeled. The probe detectors connect to the acquisition assembly via ribbon cable (one shown on the left, one on right is not connected). The bottom layer of the “three-board sandwich” houses the Altera DE0-Nano FPGA development board, which serves as the computational core responsible for real-time histogram computation on the incoming time-over-threshold (ToT) signals from all 16 detector channels. The FPGA interfaces with the middle layer through GPIO headers that carry the digital ToT input signals and control lines. The middle layer is the custom analog front-end PCB that converts analog pulses from the detectors into digital signals. Each channel includes amplification and comparison stages that produce time-over-threshold pulses encoding the deposited gamma energy. This board also generates the high-voltage bias for the SiPMs and provides temperature monitoring through an array of thermistors. The analog board connects to the external detectors via 50-pin ribbon cables. The top layer contains the Mikro-e Clicker 2 for PSoc 6 microcontroller board, which serves as the system coordinator. The microcontroller communicates with the FPGA via UART to retrieve histogram data, manages system configuration parameters, and provides Bluetooth Low Energy connectivity to the mobile application.

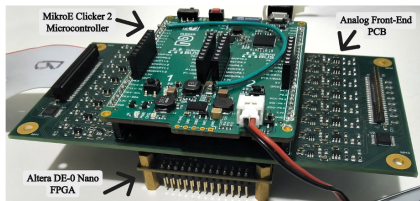


Figure 2. Photograph of “three-board sandwich.” (top) micro-controller board, (middle) analog board, (bottom) FPGA development board.

Probe Detectors

Different detector probe geometries were tested. Each detector consists of a GAGG crystal coupled to an MPPC device. In addition, a small thermistor has been added to the MPPC PCB for real time temperature monitoring of each detector assembly. Photo of different probe designs is shown in Figure 3.

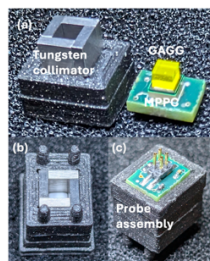


Figure 3. Photograph of γ -tube detector.

Android App

An Android mobile application serves as the primary user interface for the PODD. The application handles the complete data acquisition workflow from device discovery and connection through histogram visualization and data export. Two modes of operation are supported: user and developer. The application communicates with the microcontroller through BLE, establishing a GATT client-server architecture where the microcontroller operates as the peripheral server. Upon startup, the application scans for devices advertising the PODD service, initiates connection with MTU negotiation (requesting 512 bytes for efficient histogram transfer) and discovers available characteristics. Bidirectional handshaking ensures parameter changes are verified before subsequent operations proceed.

PODD Software

The SimSET Monte Carlo software was enhanced to support polygonal target cylinder surfaces, see Figure 1(d). The original version only supported circular target cylinders. Code has also been written to identify PODD slats in CT image files and generate SimSET parameter files for Monte Carlo simulation.

In addition, we have developed a tool for fast approximate simulation of multi-pinhole acquisition of gamma-ray photons using the PODD and direct estimation of kinetic parameters from multi-time point, multi-pinhole acquisitions using an objective function with multiple regularization terms. Using multi-time point data we treat the forward process of acquisition as a linear model given by linear combination of sensitivities of each organ of interest weighted by the average activity in the organ. The activity for each organ is a biexponential function over time. The sensitivity matrix A is obtained by applying the simulator to each region-of-interest segmentation map in the SPECT reconstruction at the first time point. The activity for each organ is a biexponential function over time. To estimate the dose over time given multiple time points, we minimize our objective function using Adam optimization. We use the initial SPECT/CT at the first time point to calibrate and regularize our estimation. Detector placement is performed by selecting a subset of detector pixels from the first time-point measurement image. For each candidate number of detectors, we identify the highest measurement locations while enforcing a minimum spatial separation distance between selected pixels. An example of our methods applied to a sample patient data set is shown in Figure 4.

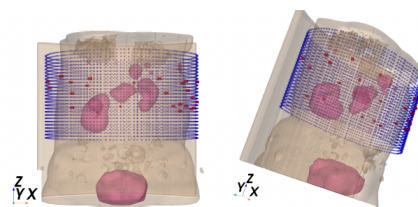


Figure 4. Rendering of the placement of pinhole collimated sensors along the envelope of CT image centered on kidney region.

III. CONCLUSION

Prototype PRRT PODD templates have been fabricated and ready for human testing. Detectors and wireless data acquisition setup have been tested. New software has been developed to support both Monte Carlo simulation of PRRT PODD workflow as well as faster running analytic simulation tools. We are evaluating the how the results comparing using the different software tools and if additional modeling needs to be included with the analytic simulator. Testing will be done using data sets from the SNMMI Dosimetry Challenge. If we have patient PODD data before the meeting results will be presented.

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