Quality assurance of radiotherapy using scattered x-ray

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Background and clinical motivation

Radiation therapy (RT) is a type of cancer treatment where a high radiation dose is delivered to a tumor with a goal of destroying it while minimizing the damage to the surrounding normal tissue. The procedures ensuring the precise and safe delivery of the dose are called Quality Assurance (QA)[1,2] and govern treatment planning (contour delineation, dose calculation, etc.), treatment verification (dose transport simulation, physical tests with dosimeters and phantoms, etc.), and treatment delivery (equipment calibration, patient positioning, motion management, etc.). Our project focuses on the treatment verification aspect of QA. When verifying a RT treatment plan, medical physicists compare the delivered radiation dose to the prescribed dose using various techniques. Thus, for example, in absolute dosimetry[3,4], physicists locate an ionization chamber at a certain depth of a slab phantom to obtain the dose measurement at that location. In reference dosimetry[5], they place a radiochromic film inside a phantom. After radiation exposure, physicists correlate the resultant film density with the delivered dose using a film-dosimetry software. When performing *in vivo* dosimetry[3], physicists measure the dose at skin by installing thermoluminescent dosimeters on a patient’s body.

Knowing the dose at surface is not sufficient for a comprehensive RT treatment verification. Obtaining a point dose inside a phantom does not provide with understanding of a complete depth dose distribution as well. Furthermore, the dosimetry in a real human body having heterogeneous density differs from the dosimetry in homogeneous phantoms[3]. Given that no films and chambers should be placed inside patients, there is a need for a QA technology allowing to verify a dose distribution in a medium outside of a phantom/patient, ideally in real time[6]. And that is where our project comes in.

Project goal and deliverables

The project goal is to implement a new QA method for RT using scattered x-ray registration.

Deliverables

Minimum:	Incorporation of the detector section into the existing Monte Carlo radiation transport simulation package[7,8] (the gDPM)
Expected:	1. Detector performance verification 2. Depth dose profile simulation
Maximum:	Simulated depth dose profile verification

Technical approach

The project work environment is Monte Carlo (MC) Simulation of megavoltage (MV) radiation transport into a medium. For each individual photon, the simulation takes its position, direction, and velocity as inputs, and uses a random number generator and probability distributions for different types of photon interactions with the medium to sample the distance to the next interaction[9]. Then, the process is repeated until the energy of primary and scattered photons is depleted. In the case of MV x-rays, the absorption of photons in a medium happens mainly due to the Compton process[10] where an incident photon interacts with a planetary electron having a low binding energy. The photon gives a part of its energy to the electron as kinetic energy. Then, it deflects from its original path, proceeds with reduced energy, and gets involved in further interactions. The project is based on the idea that an external registration of these Compton scattered photons might provide the information about the depth dose distribution[6].

The diagram in Figure1 depicts a MV x-ray beam applied to a water phantom. While the beam passes through the medium, many photons undergo Compton scattering. A photon counting detector is placed next to the phantom to register the scattered photons. Once the registration is modeled, the challenge here is to relate the detector signal to the delivered radiation dose.

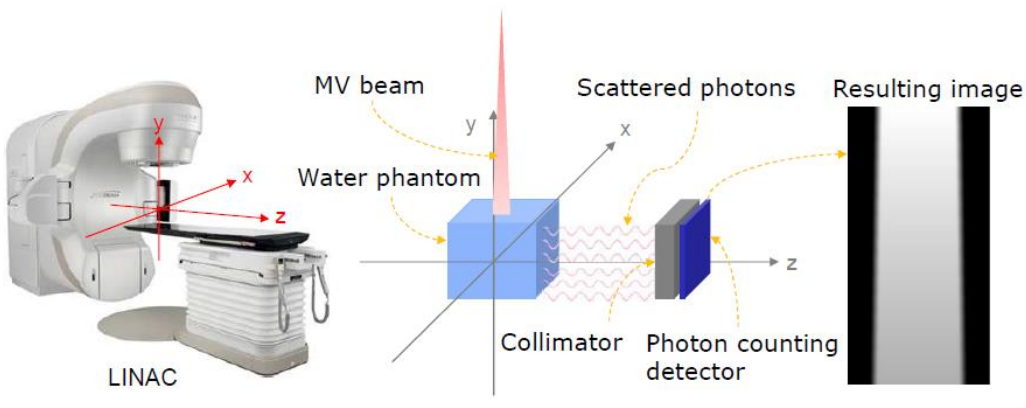

Fig. 1. The diagram of RT QA method using scattered x-ray registration[6]

In order to create a virtual photon counting detector, we will first extract the trajectory of each photon from the MC Simulation and record the angle at which photons exit the phantom. Then, we will filter the photons based on the angle to distinguish the ones that would fall onto the detector sensor, thus modeling the signal the detector would receive in the physical world while having a collimator placed in front of it. Next, we will record the deposited energy along the trajectories of the detected photons to further relate it to the detector signal. Testing the photon counting detector will be done against previous kV x-ray physical measurements[11,12] while the verification of the detector signal to dose relationship will be performed alongside MV x-ray physical experiments conducted by our mentors. Figure 2 displays the technical approach overview emphasizing the main work milestones.

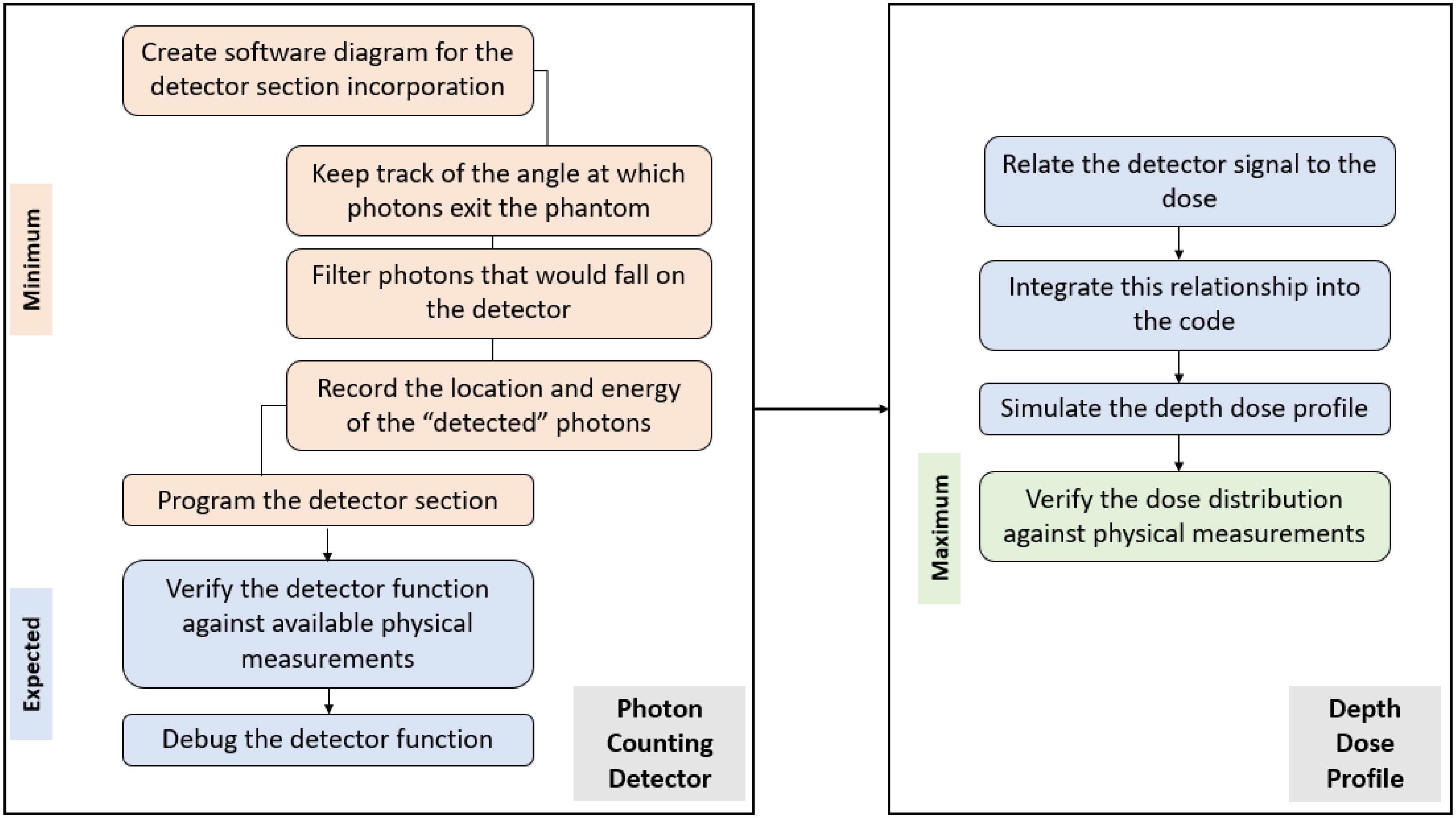

Fig. 2. Technical approach overview

Key dates & Responsibilities

Samuel and Tatiana will work on the project together during their meetings. If it turns out to be easier to divide some parts of the work, then they will perform their designated tasks individually and discuss the results on the closest meeting.

Project Deliverable		Activities	Output (submit in the team's chat)	Deadline Soft (Hard)	Status
Minimum	Incorporation of the detector section into the existing MC radiation transport simulation package[7,8] (the gDPM)	1. Perform literature review on QA, Cherenkov Imaging, and Photon counting; study the gDPM package documentation	A written 1-1.5-page summary to use in the final project report	02/20 (02/23)	Done on 02/17
		2. Address the corresponding dependences and make sure that CUDA drivers are installed correctly	Screenshots of successful runs of the first two examples in CUDA samples	02/20 (02/23)	Done on 02/15
		3. Compile the gDPM on our machine	Statistical comparison of our and our mentors' simulation results with the same input parameters	02/24 (02/27)	Done on 02/21
		4. Create a plan for incorporating the detector into the gDPM code	A block diagram of the desired code structure	03/10 (03/12)	In progress
		5. Program the detector section based on the designed block diagram	C code with comments, a plot of the registered scattered x-rays	03/17 (03/19)	Not started
		6. Document the code	PDF document	03/20 (03/21)	Not started

Key dates & Responsibilities (continued)

Project Deliverable		Activities	Output (submit in the team's chat)	Deadline Soft (Hard)	Status
Expected	Detector performance verification	1. Adjust the simulation to match the setup of the previous kV x-ray scattered photon registration experiments[11,12]	C code with comments	03/28 (03/29)	Not started
		2. Document the setup parameters	PDF document	03/28 (03/29)	Not started
		3. Compare the simulation and experimental data	MATLAB code with comments and data visualizations	03/29 (03/30)	Not started
		4. Debug the detector section code until the simulation data match the experimental data with 5-8% accuracy	Refined detector code	04/06 (04/07)	Not started
		5. Document the data comparison methodology and the discussion of the results	PDF document	04/07 (04/08)	Not started
	Depth dose profile simulation	1. Relate the detector signal to the delivered dose based on the mentor's guidance	Mathematical expression(s)	04/20 (04/21)	Not started
		2. Integrate the relationship into the simulation code	C code with comments, a plot of the depth dose profile	04/24 (04/25)	Not started
		3. Document the relationship and the code	PDF document	04/24 (04/25)	Not started

Key dates & Responsibilities (continued)

Project Deliverable		Activities	Output (submit in the team's chat)	Deadline Soft (Hard)	Status
Maximum	Simulated depth dose profile verification	1. Adjust the simulation to match the setup of the prospective MV x-ray QA experiments following the mentor's guidance	C code with comments	04/25 (04/26)	Not started
		2. Document the setup parameters	PDF document	04/25 (04/26)	Not started
		3. Compare the simulation and experimental data	MATLAB code with comments and data visualizations	04/27 (04/28)	Not started
		4. Document the data analysis methodology and the discussion of the results	PDF document	04/27 (04/28)	Not started
CIS II	Fulfillment of the final class requirements	1. Make the project poster presentation	Poster presentation in PDF	Exam date in May	Not started
		2. Write the final project report	Project report in PDF		

Dependencies

Need	Dependencies	Source	Responsible	Deadline Soft (Hard)	Status	Contingency Plan
General	Computer with a CUDA-capable GPU	Dr. Mohammad Rezaee	Tatiana	02/03 (02/07)	Done on 01/31	NA
	Remote access to the computer for Samuel	JHU IT	Tatiana	02/10 (02/13)	Done on 02/08	NA
The gDPM compilation	The gDPM simulation package	Dr. Youfang Lai, Dr. Yujie Chi	Dr. Lin Su	02/10 (02/13)	Done on 02/09	NA
	Google Colab	Google	Samuel	02/13 (02/15)	Done on 02/13	NA
Comparison of the simulated depth dose profile with physical measurements	Physical measurements	Dr. Xun Jia, Dr. Lin Su		04/20 (04/25)	Not started	Do in summer if possible

Management Plan

Samuel and Tatiana will meet on Monday, Wednesday, and Friday via Zoom or at JHH for 2-3 hours as well as on Tuesday and Thursday on JHU Homewood for 1.5 hours before or after the class. They will communicate with the Dr. Su and Dr. Jia weekly via JHU email and Microsoft Teams group chat and meet virtually via Microsoft Teams when needed. The mentors in the technical support team will be contacted when there are questions about the gDPM simulation package as those people took part in its development. File sharing will be done via JHU OneDrive, JHU email and Microsoft Teams group chat.

Reading List

- QA[1,2,3,4]
- Cherenkov imaging:
    - Miao, T., Bruza, P., Pogue, B. W., Jermyn, M., Krishnaswamy, V., Ware, W., Rafie, F., Gladstone, D. J., & Williams, B. B. (2019). Cherenkov imaging for linac beam shape analysis as a remote electronic quality assessment verification tool. *Medical Physics*, *46*(2), p. 811–821. doi: 10.1002/mp.13303
    - Pogue, B.W., Zhang, R., Glaser, A., Andreozzi, J.M., Bruza, P., Gladstone, D.J., & Jarvis, L.A. (2017). Cherenkov Imaging in the Potential Roles of Radiotherapy QA and Delivery. *Journal of Physics: Conference Series, 847*, p. 012046. doi: 10.1088/1742-6596/847/1/012046
- Photon counting[10,11]:
    - Huang, Y., Hu, X., Zhong, Y., Lai, Y., Shen, C., & Jia, X. (2021). Improving dose calculation accuracy in preclinical radiation experiments using multi-energy element resolved cone-beam CT. *Physics in Medicine and Biology*, *66*(24), p. 245003. doi: 10.1088/1361-6560/ac37fc
- gDPM Simulation package[6,7]

References

1. World Health Organization. (1988). Quality Assurance in Radiotherapy: a Guide Prepared Following a Workshop Held at Schloss Reisensburg, Federal Republic of Germany, 3-7 December1984. Geneva.
2. Glide-Hurst, C.K., & Chetty, I.J. (2014). Improving radiotherapy planning, delivery accuracy, and normal tissue sparing using cutting edge technologies. *Journal of Thoracic Disease*, *6*(4), p.303–318.doi:10.3978/j.issn.2072-1439.2013.11.10
3. Gurjar, O.P., Mishra, S.P., Bhandari, V., Pathak, P., Patel, P., & Shrivastav, G. (2014). Radiation dose verification using real tissue phantom in modern radiotherapy techniques. *Journal of Medical Physics*, *39*(1), p.44–49.doi:10.4103/0971-6203.125504
4. Kumer, T., Das, P., Khatun, R., Rahman, Md., Akter, S., & Kumar Roy, S. (2021). Comparative Studies of Absolute Dose in Water Phantom, Solid Water Phantom and MatriXX with MULTICube Phantom. *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology*, *10*(4), p. 169-177. doi: 10.4236/ijmpcero.2021.104014
5. Khachonkham, S., Dreindl, R., Heilemann, G., Lechner, W., Fuchs, H., Palmans, H., Georg, D., & Kuess, P. (2018). Characteristic of EBT-XD and EBT3 radiochromic film dosimetry for photon and proton beams. *Physics in Medicine and Biology*, *63*(6), 065007. doi: 10.1088/1361-6560/aab1ee
6. Jia, X. (2023). Quality assurance of radiotherapy treatment using scattered x-ray. Presentation slides for CIS II
7. Jia, X. & Jiang, S.B. (2011). gDPM v2.0. A GPU-based Monte Carlo simulation package for radiotherapy dose calculation. The Center for Advanced Radiotherapy Technologies (CART), UCSD.
8. Jia, X., Ziegenhein, P., & Jiang, S. B. (2014). GPU-based high-performance computing for radiation therapy. *Physics in Medicine and Biology*, *59*(4), p. R151–R182. doi: 10.1088/0031-9155/59/4/R151
9. The Netherlands Commission on Radiation Dosimetry. (2006). Monte Carlo treatment planning. An introduction. Report 16.

10. Hall, E.J. (2000). Radiobiology for the radiologist. 5th edition. Philadelphia, PA: Lippincott Williams & Wilkins.
11. Hu, X., Zhong, Y., Lai, Y., Shen, C., Yang, K., & Jia, X. (2022). Small Animal Photon Counting Cone-Beam CT on a Preclinical Radiation Research Platform to Improve Radiation Dose Calculation Accuracy. *Physics in Medicine and Biology, 67*(19), p. 195004. doi:10.1088/1361-6560/ac9176
12. Hu, X., Zhong, Y., Yang, K., & Jia, X. (2022). Photon Counting Detector-Based Multi-Energy Cone Beam CT Platform for Preclinical Small Animal Radiation Research. *Proc. SPIE 12304, 7th International Conference on Image Formation in X-Ray Computed Tomography*. doi: 10.1117/12.2647036