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Final Report – Tianxue Du

Starting Point and Objectives

From March to May 2026, I spent three months at the National Institutes for Quantum Science and Technology (QST) in Chiba, Japan, in the group of Prof. Taiga Yamaya, supported by the Wolfgang Schlegel Scholarship of the DGMP. The aim of the stay was to apply an analytical method for predicting PET images, which I had developed during my PhD at LMU Munich in the group of Prof. Katia Parodi, to in-beam PET data from carbon ion therapy and to validate it there.

Particle therapy is highly conformal thanks to the Bragg peak, but for the same reason it is sensitive to range uncertainties: even small deviations in the particle range can lead to underdosage of the tumour or overdosage of healthy tissue. In-vivo range verification is therefore highly desirable, and PET is one of the most established techniques for this purpose. Because the PET signal is not proportional to the dose, the measurement has to be compared with a predicted PET image. That prediction can come from a Monte Carlo simulation, which is accurate but slow, or from analytical methods, which are far faster and therefore applicable in clinical routine. Our work follows the analytical route.

Three concrete objectives were pursued during the stay:

- Objective 1: Re-parameterise the model using the simulated data generated at QST, covering both the parameters of the 1D positron emitter depth distributions and those of the lateral distributions.
- Objective 2: Validate the updated model against phantom measurements of the in-beam PET system OpenPET.
- Objective 3: Apply the method to a real patient case treated at HIMAC.

Implementation

The method is based on a pencil beam algorithm. Starting from the dose distribution together with phantom and beam information, the laterally integrated depth dose is first obtained in a reference material composed of six elements and converted analytically into laterally integrated depth distributions of five positron emitters. The pencil beam algorithm then spreads these 1D distributions laterally to build the full three-dimensional distribution of positron emitters. Modelling radioactive decay, biological washout and the spatial resolution of the scanner finally yields a realistic activity map. The framework was first validated on clinical cases from the Heidelberg Ion-Beam Therapy Center (HIT) using offline PET, with the distribution computed spot by spot for the whole treatment plan.

At QST, the in-house developed in-beam PET system OpenPET was available. The model was first re-parameterised with PHITS Monte Carlo simulation data from QST and then used to predict in-beam PET data of a PMMA phantom. The method was then applied to a head-and-neck patient treated with carbon ions at HIMAC. Irradiation used two fields, a vertical one with 43 energy layers and a horizontal one with 50 layers, each comprising around seven thousand spots. The PET acquisition started after the first field had been delivered, and the images were reconstructed from the end of the second irradiation onwards. Compared with the approach used at HIT, the calculation for patient cases was simplified and adapted: instead of calculating a separate positron emitter distribution for every spot, the calculation looped over energy layers. The CT conversion followed Kanematsu's method, which is consistent with the HIMAC treatment planning system.

Results

With the updated model the PMMA calculation was evaluated for three measurement time windows (0–1 min, 5–10 min and 0–10 min). The plateau region and the distal fall-off, which reflects the range, were well reproduced. For a 4 × 4 cm² irradiation field, the prediction reproduced both the shape and the intensity level of the measurement reconstructed over 10 minutes.

In the patient case as well, the location, shape and intensity level of the predicted activity distribution agreed well with the measurement. For a more quantitative assessment, 1D profiles were extracted along the beam direction for each field: the analytical prediction followed the measured profile closely, and the distal fall-off was well reproduced. Considering the complexity of a real patient case, including heterogeneous anatomy, biological washout and the conditions of an in-beam measurement, this level of agreement is very encouraging.

Discussion

In the earlier time windows, the in-beam PET signal was dominated by short-lived positron emitters, which offline PET cannot reveal because it mainly probes the long-lived emitters. For the clinical use of in-beam PET, the yields of the short-lived emitters must therefore be validated separately against in-beam data, as was done during this stay.

Remaining uncertainties lie mainly in the modelling of biological washout and the measurement noise. In addition, the patient evaluation so far rests on a single case, so no conclusions about inter-patient variability can be drawn yet.

Conclusion and Outlook

All three objectives were met: the model was re-parameterised with the PHITS simulation data, validated against phantom measurements and successfully applied to a first patient case from HIMAC. This provides a validation of the framework on in-beam data that goes substantially beyond the previous offline validation. Being fast and lightweight compared with Monte Carlo, the method is a promising candidate for routine clinical range verification. As a next step it will be applied to further HIMAC patient cases.

Personally, I take away from these three months above all methodological competence in handling in-beam PET data, an insight into how a Japanese research group works, and an ongoing collaboration with QST. The expectations with which I began the stay have been met.

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For questions about my project and my experience, my contact details can be requested from the DGMP.