OpenPET: a novel open-type PET system for 3D dose verification in particle therapy

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Abstract. The OpenPET is the world’s first open-type 3D PET scanner for PET image-guided particle therapy such as in situ dose verification and direct tumour tracking. Even with a full-ring geometry, the OpenPET has an open gap between its two detector rings through which the treatment beam passes. Following the initial proposal of the dual-ring OpenPET (DROP), the single-ring OpenPET (SROP) was also proposed as a more efficient geometry than DROP in terms of manufacturing cost and sensitivity. A small SROP prototype was developed and feasibility of visualizing a 3D distribution of beam stopping positions inside a phantom was shown with the help of radioisotope particle beams, used as primary beams. Following these results, a full-size whole-body SROP prototype was developed.

1. Introduction
Cancer is a major cause of death in developed nations, and the disease death rate continues to increase. Therefore, many efforts have been made toward better diagnosis and better treatment. Among diagnostic methods, positron emission tomography (PET), which can visualize functions such as metabolism by injecting radioisotope tracers labelled with positron emitters, is expected to enable earlier and more precise cancer diagnosis.

For treatment, on the other hand, radiotherapy is essential for effective cancer treatment with minimized side effects. Specifically, particle therapy such as proton and carbon ion therapy are expected to be the ultimate radiotherapy because they can concentrate the dose even in a deep tumour. Thus there has been remarkable progress in PET and radiotherapy, but no one has looked into the great potential to be obtained by the combination of both.

An open-type PET geometry (OpenPET) is a new idea to visualize a physically opened space between two detector rings [1], which will move researchers toward a future joint PET imaging and radiotherapy system. OpenPET is expected to achieve in-beam PET, which is a method to monitor in situ charged particle therapy. Without injecting any PET tracer, positron emitters are produced through fragmentation reactions between the projectiles and the atomic nuclei of the tissue during patient irradiation [2-3]. Compared with conventional radiation therapy, charged particle therapy can highly concentrate the dose in a tumour. This means if there is any difference between the actual irradiation and the treatment plan, the tumour treatment will be compromised, and the normal tissue around the tumour will be damaged. Therefore, quality of treatment must be assured by in-beam PET.
2. Simulation and system design

We have proposed two geometries for OpenPET: dual-ring OpenPET (DROP) [1] and single-ring OpenPET (SROP) [4]. Figure 1 shows a conceptual illustration of the SROP comparing with the DROP and a conventional PET which is positioned at a slant angle relative to the bed to form an accessible space (hereinafter referred to as “slant PET”) [5]. Compared with the slant PET, the SROP is expected to provide higher sensitivity with a smaller number of detectors. Thus, in the case of in-beam PET, provides a closer positioning of the beam port, which minimizes beam broadening.

We calculated the geometrical sensitivity at the centre. As fixed parameters, the bed width of 600 mm and open gap of 300 mm were selected to provide a sufficient open space during ion-beam therapy. Here, we assumed that the area of the block-detector was 2500 mm² (i.e., 50 mm × 50 mm). When the detector surface area was 500,000 mm², in which the equivalent number of block-detectors was 200, the geometrical sensitivities of the SROP, DROP and slant PET were 27.8%, 23.9% and 22.1%, respectively. The SROP can provide an accessible and observable open space with higher sensitivity and a reduced number of detectors compared to the previous generation geometries.

![Figure 1. Conceptual illustrations of PET geometries with an accessible open space to the patient.](image)

3. Development of a small prototype

Figure 2 shows a small SROP prototype [6], which had two open and closed modes. The open mode formed the SROP geometry and the closed mode formed the conventional cylindrical PET geometry. Sixteen detector units each of which consisted of two depth-of-interaction (DOI) detectors were arranged to form a perfect circle with a diameter of 250 mm. Each DOI detector consisted of a H8500 PMT and the 4-layer 16 × 16 array of Zr-doped GSO (GSOZ) scintillators with a size of 2.8 × 2.8 × 7.5 mm³. Detector units had an axial-shift mechanism so that they could be transformed into the SROP having an open space of 139 mm. In the open mode, the centre of each detector surface, positioned on
the parallel planes, was slanted 45° against the axial direction. For shifting purposes, each detector unit was connected to the neighbouring detector units by linear guides. Transformation between the cylindrical PET and the SROP, which was controlled by one rotation handle was completed within 10s.

We evaluated the basic performance of the prototype. The spatial resolution and sensitivity were 2.6 mm and 5.1% for the open mode and 2.1 mm and 7.3% for the closed mode. The SROP enables in-beam PET imaging at a slight cost of imaging performance. The decrease of the performance can be minimized, for example, by transforming into the close mode immediately after the irradiation, while maintaining the open space only for the in-beam PET measurement.

4. In-beam imaging of carbon ion beam

The small prototype was brought into the heavy ion medical accelerator in Chiba (HIMAC), where we conducted the in-beam imaging tests. A PMMA phantom was irradiated with an RI beam of $^{11}$C, which has a half-live of about 20 min. The RI beam was generated as a secondary beam from the $^{12}$C irradiation onto a Be target [7]. Figure 3 shows the experiment setup. The dimensions of the rectangular cuboid PMMA phantom were $40 \times 40 \times 100$ mm$^3$ and an additional PMMA board with a thickness of 9 mm was used to cover the upper half of the beam. The irradiation time was about 10s and a dose of about 2.5 Gy was given. The beam intensity was about $5 \times 10^6$ particles per second and the beam energy was 340 MeV/u. Therefore, the Bragg peak position in PMMA was at 168 mm. A PMMA range shifter of 115 mm thickness was used so that the Bragg peak position was moved to 53 mm from the entrance of the phantom. PET data were measured during the irradiation and for 20 minutes after the irradiation ended. Because the irradiation beam in the HIMAC had a cycle of 3.3 s with beam-on time (spill-on) of

![Figure 3. Setup for PMMA phantom irradiation by the $^{11}$C beam and in-beam PET measurements. A photograph of the setup (a) and illustrations for front (b) and top (c) views are shown.](image)

![Figure 4. Imaging results of the 9 mm difference given by the Bragg peak positions: the 3D visualization of the image with the shape of the PMMA phantom (left) and profiles along the beam direction (right).](image)

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about 1.8 s and a beam-off time (spill-off) of about 1.5 s, PET data for the spill-off time were extracted. The 3D list-mode maximum likelihood expectation maximization (LM-MLEM) was employed for the PET image reconstruction. The number of iterations was 50 and the voxel size was $1.5 \times 1.5 \times 1.5$ mm$^3$. Random correction and attenuation correction were applied but scatter correction was not applied because the phantom size was small enough so that the scatter effects can be ignored.

Figures 4 shows images reconstructed from counts measured between spills and for 20 minutes after the irradiation. The number of counts was 626 k counts. Figure 4 also shows the profiles of single voxel lines along the beam direction for the upper part with the 9 mm PMMA board and for the lower part without it. The peak position of the lower part was calculated by parabola fitting as 55.0 mm (planned Bragg peak at 53 mm). The difference in peak positions was clearly observed and measured as 8.8 mm, which was almost the same as the given difference. Following proof-of-concept results, a full-size whole-body SROP prototype was developed (figure 5).

5. Conclusion
This paper described basic concepts and prototypes of the OpenPET, which led to the world’s first open-type 3D PET scanner. The SROP is a more efficient OpenPET geometry in terms of the gap size and the sensitivity. Demonstrations with a prototype showed a proof-of-concept of PET-image guided particle therapy such as in situ dose verification.

6. References
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