Fast Positron Distribution Scoring with MCsquare for PET-Based Proton Range Verification

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ABSTRACT

Purpose: PET-based proton range verification is promising but limited by the computational cost of current Monte Carlo methods. We developed MC²-PE, a dedicated positron-scoring module within the optimized MCsquare framework for fast, simultaneous simulation of dose and positron emitters. **Methods:** Activation cross-sections for the dominant tissue elements (^{12}C, ^{14}N, ^{16}O) were integrated to compute voxel-wise isotope production, then validated against GATE in homogeneous and heterogeneous phantoms. **Results:** MC²-PE showed high spatial agreement with GATE in dose (R_{80}) and positron-yield profiles (^{11}C, ^{15}O, ^{13}N), while achieving a 40–160× reduction in runtime. **Conclusions:** MC²-PE provides an efficient, concurrent solution for dose and isotope calculation, with strong potential to improve treatment precision; patient-specific validation is ongoing.

KEY HIGHLIGHTS

40–160×

faster than GATE/GEANT4 Monte Carlo

- Concurrent dose & positron-emitter simulation
- Validated vs. GATE/GEANT4 in homogeneous & heterogeneous phantoms
- Efficient path toward patient-specific translation

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PURPOSE

- Proton therapy is increasingly central to cancer treatment, but range uncertainty challenges accurate targeting of tumors while sparing normal tissue.
- PET enables **in vivo** range verification by imaging proton-activated positron emitters to estimate the delivered dose.
- Current Monte Carlo methods for PET-based verification are severely limited by computational inefficiency.
- This study integrates a proton-induced positron-emitter production model into the optimized MCsquare framework for fast, accurate, simultaneous simulation of dose and positron-emitter distributions.

METHODS AND MATERIALS

- Implemented **MC²-PE**, a dedicated positron-scoring module built on the optimized MCsquare Monte Carlo platform.
- Curated activation cross-sections for the dominant tissue elements (**^{12}C, ^{14}N, ^{16}O**) across six key reaction channels, integrated as cross-section tables to compute isotope-specific production rates alongside dose deposition.
- Validated MC²-PE against GATE Monte Carlo in both homogeneous and heterogeneous phantoms.
- Quantified computational efficiency (MCsquare vs. GATE) and the consistency of dose and positron-activity distributions.

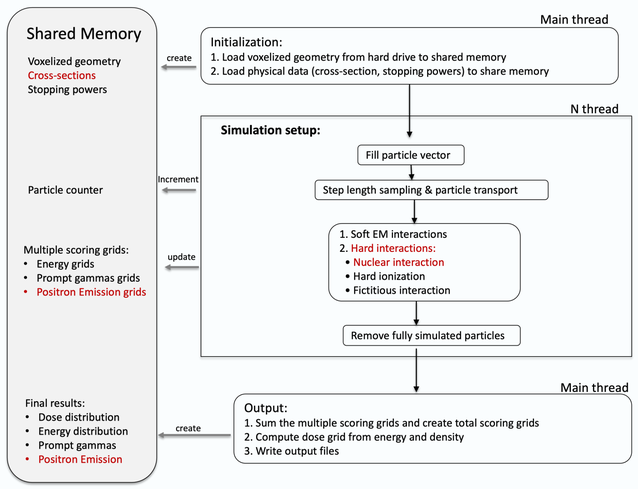

Figure 1. Overall MCsquare simulation framework

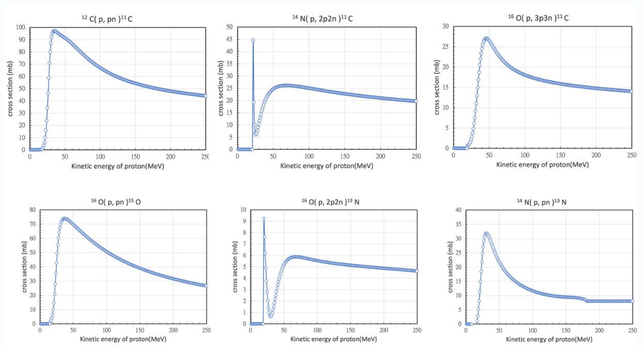

Figure 2. Energy-dependent nuclear reaction cross-sections for the production of ^{11}C, ^{15}O, and ^{13}N.

RESULTS & DISCUSSION

- Dose distributions reproduced GATE with high consistency in R_{80} range.
- Depth-yield profiles of the dominant positron emitters (^{11}C, ^{15}O, ^{13}N) agreed closely with GATE in both homogeneous water and heterogeneous phantoms.
- MC²-PE achieved a **40–160× reduction in runtime** versus GATE across varying numbers of primary histories using voxel-based phantoms.

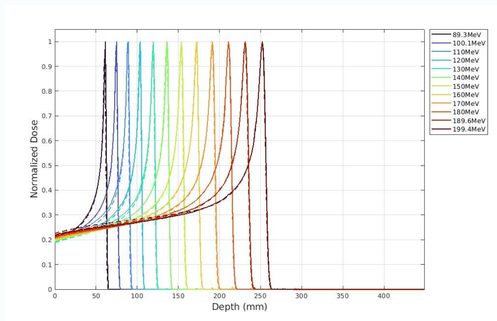

Figure 3. Depth-dose distributions of proton beams simulated by the MCsquare and GATE platforms.

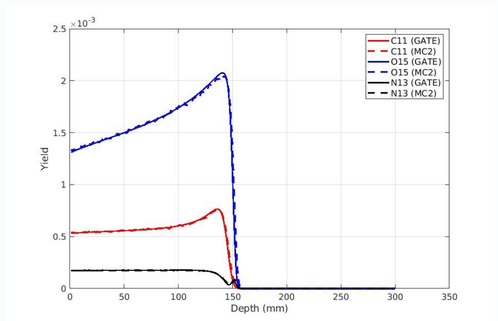

Figure 4. Comparison of positron yield depth profiles predicted by MCsquare and GATE.

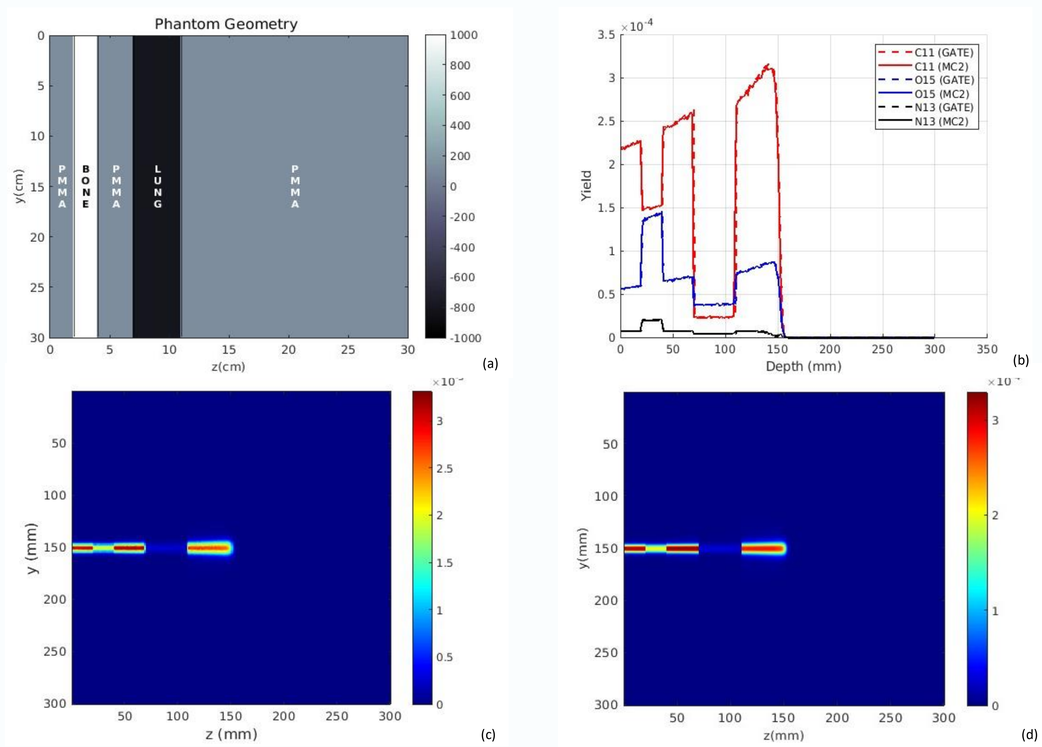

Figure 5. Simulation results in a heterogeneous phantom. (a) Phantom geometry consisting of PMMA, bone, and lung equivalent materials. (b) Comparison of positron yield depth profiles between MC²-PE and GATE. (c) 2D positron emission distribution(C11) calculated by MC²-PE. (d) 2D positron emission distribution(C11) simulated by GATE.

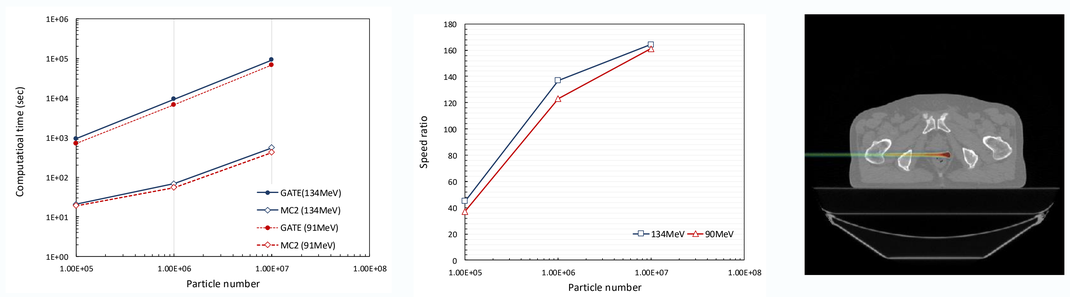

Figure 6. Performance comparison of MC²-PE and GATE. (a) Computation time, (b) Speed ratio, and (c) Simulation scenarios.

CONCLUSIONS

- MC²-PE enables rapid, accurate PET-based range verification through concurrent dose and isotope calculation.
- Validated for accuracy in both homogeneous and heterogeneous phantoms, with strong potential to enhance treatment precision.
- Future work: evaluation on patient-specific data toward routine clinical translation.

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