Monte Carlo simulation of out-of-field dose distribution in carbon-ion radiotherapy with passive beam

Shunsuke YONAI, Naruhiro MATSUFUJI, Masao NAMBA
1) National Institute of Radiological Sciences, 4-9-1, Angawa, Inage-ku, Chiba, Japan
2) Yokohama City Univ., 3-9, Fukaura, Kanazawa-ku, Yokohama, Kanagawa, Japan
(Present: Japan Radioisotope Association)
(E-mail: yonai@nirs.go.jp)

INTRODUCTION
- The secondary cancer risk of patients receiving radiotherapy depends on the volume both of the high-dose region in the irradiation field (in-field volume) and of the low-dose region outside the field (out-of-field volume).
- Secondary cancer risk in the low-dose region has remained controversial, but it may be not negligible for risk assessment, especially in younger patients.
- The out-of-field dose during ion beam radiotherapy is being continuously investigated. Our previous studies on the out-of-field doses in carbon-ion and proton radiotherapies were comparable to or lower than those in 3DCRT and IMRT. In particular, as the position became closer to the field edge, the doses were obviously lower than those in 3DCRT and IMRT.
- Now, our concern has shifted to routine risk assessment of each patient receiving carbon-ion radiotherapy and an epidemiological study for the more than 6000 patients who have received carbon-ion radiotherapy with passive beam at National Institute of Radiological Sciences (NIRS).
- The dose estimation for each patient is essential for risk assessment and an epidemiological study. Monte Carlo simulation plays an important role because the currently employed treatment planning system can provide dose distribution only in the irradiation field and the measured data are limited.

OBJECTIVES
- This study is the first step toward routine risk assessment and an epidemiological study on carbon-ion radiotherapy with passive beams.
- Primary purpose:
  - To establish a calculation method with the Monte Carlo code to estimate the out-of-field dose in the body and validate the method by comparing its results with our experimental data.
- Furthermore, we show the distributions of dose equivalent in a phantom and identify the partial contribution of each radiation type.

METHODS
1. Method to estimate absorbed dose, quality factor and dose equivalent
   - The radiation weighting factor of an equivalent source for the purpose of secondary cancer risk calculation in proton radiotherapy was estimated based on the neutron energy at the surface of each organ.
   - The neutron energy spectrum and the result was estimated by measurement in the present technology.
- Quality factor, Q and dose equivalent, H were used in this study.
- Monte Carlo code PHTS
  - Tails.
  - The following three tails were used:
    1. Sextetal.
    2. Sextetal.

2. Validation of the calculation method
   - The experiment performed in Ref. 2 was modeled in this calculation.
   - The 12.5mm-diameter sphere of AE150 plastic was modeled at the measured positions in the water phantom as the tally volume.

RESULTS AND DISCUSSION
1. Validation of the calculation method
   - The strayed charged particles contributed to D, H and Q at positions more than 50 cm from the field edge.
   - The strayed charged particles are expected to be composed of secondary protons with strong scattering power; therefore, it decreases the quality factors.
   - Calculations will exclude the strayed charged particles from the beam nozzle fabricated here on.
   - The result calculated without strayed charged particles, the measured (Q) agreed well with the calculation without strayed charged particles, and consequently the measured H agreed well with the calculation with strayed charged particles.
   - The contribution of the strayed charged particles is expected to be quite low in practice because there was equipment that could not be modeled in the calculation.

2. Distributions of dose equivalent in phantom at the I.C. height
   - H from external neutrons decreased when the position became farther from the field edge and the phantom surface (and became larger).
   - H from all radiation types except charged particles decreased mainly when the position became farthest from the field edge (and became larger). The differences depend on the difference in positions where the secondary radiations are produced: secondary charged particles and internal neutrons are produced in the phantom by the primary carbon beam; and external neutrons are produced mainly in the air.

3. Partial contribution of each radiation type to the total dose equivalent
   - External neutrons became the first contributor to H at a distance further than about 10 cm from the field edge at 20-22 cm depth.
   - The contribution of external neutrons was higher when the position was closer to the phantom surface.
   - The contributions of secondary protons and internal neutrons were higher when the position moved deeper into the phantom, because secondary protons and internal neutrons are produced in the short reaction distance due to the direct reaction process along the beam path.

4. Passive beam vs. Active beam
   - H from all radiation types except external neutrons corresponds roughly to that by the active scanning beam.
   - Assuming two opposed equally-weighted 200MeV/u beams, the increase with the passive beam compared to the active beam reached up to 3.3 mSv/Gy, corresponding to 78 mSv per single treatment (RBE: 2.36, Prescribed dose for a typical prostate cancer treatment at HIMAC: 57.6 GY (20-66Gy/16 fractions)).

CONCLUSIONS
- We proposed a calculation method with the PHTS code to estimate the distribution of dose equivalent in the body.
- The validation method can be used to approximate the secondary cancer risk outside the beam path not only in carbon-ion radiotherapy but also in proton radiotherapy regardless of the passive and active beams.

References:
5. S. Yama et al., Development of passive-carbon-Particle and Heavy ion (Transmarc Monte Carlo code), Cancer. 11, 1416-1431 (2002).