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

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INTRODUCTION

- The secondary cancer risk of patients receiving radiotherapy depends on the volumes 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.[1,2] Our previous studies the out-of-field doses in carbon-ion and proton radiotherapies were comparable to or less than those in 3D-CRT and IMRT. In particular, as the position became closer to the field edge, the doses were obviously less than those in 3D-CRT 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/near the irradiation field and the measured data are limited.

OBJECTIVES

- This study is the first step toward routine risk assessment and an epidemiological study of 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[2].
- 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 w_R and equivalent dose are commonly used for the purpose of secondary dose assessment in proton radiotherapy.[3,4]
  - → w_R was estimated based on the neutron energy at the surface of each organ.
  - → The neutron energy spectrum and the resultant w_R cannot be verified by measurement in the present technology.
  - → Quality factor, ***Q*** and dose equivalent, ***H*** were used in this study.
- Monte Carlo code: **PHITS**
- Tallies: The following three tallies were used.
  1. Heat tally, T_h for calculating the energy deposit from all radiation species into the volume of interest.
  2. Deposit tally, T_d for calculating the energy deposit into the volume of interest due to charged particles including those produced by neutrons.
  3. Deposit tally with the "dedxfnc" option in the PHITS code, T_{dd} for calculating $\sum_i (Q_i \cdot D_i)$ by charged particles including those produced by neutrons. (Q_i and D_i are the quality factor and the absorbed dose for an event, *i*, respectively.)
- The *Q*(*L*)-*L* relationship is used based on the ICRP 60 recommendation.
  - *L* of charged particles was assumed to be same as the stopping power, *dE/dx*.
  - *L* of photons was assumed to be less than 10 keV m^{-1}.
- *D*, *H* and Q_D were obtained as follows:

$$D = T_h \qquad Q_D = (T_{dd} + (T_h - T_d))/T_h \qquad H = T_{dd} + (T_h - T_d)$$

2. Validation of the calculation method

- The experiment performed in Ref. 2 was modeled in this calculation.
- The 12.7-mm-diameter spheres of A-150 plastic were modeled at the measured positions in the water phantom as the tally volume.

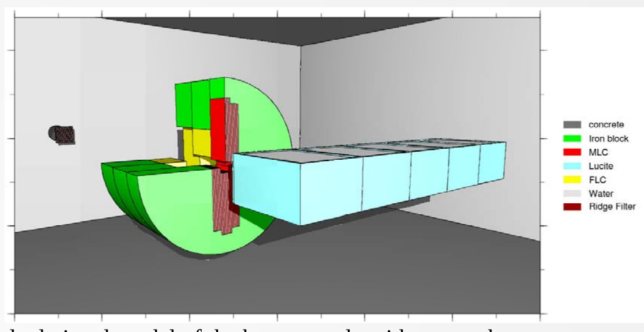


Fig.: Calculational model of the beam nozzle with water phantoms. (A part of the beam nozzle was made transparent here.)

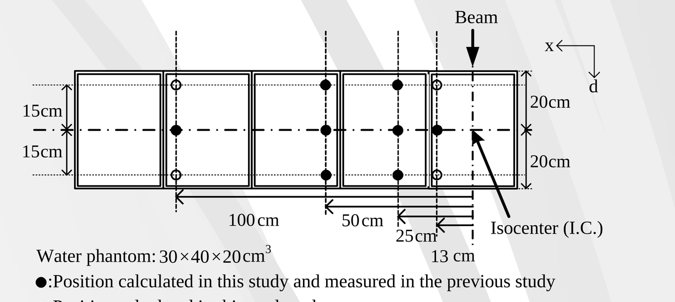


Fig.: Cross-sectional view of water phantoms and calculation positions.

Table: Parameters in the beam line devices used in this study

Beam Energy [MeV/u]	Diamter of laterally-uniform irradiation field [mm]	SOBP width [mm]	Aperture size of the adjustable FLC [mm²]	Distance between the downstream surface of the MLC and the IC [mm]	Aperture size of the MLC [mm²]
290/400	100	60	78.1 × 70.0	500	58.1 × 50.0

3. Distributions of dose equivalent in phantom at the I.C. height

- Phantom material: Average soft tissue of an adult male defined in ICRU 44.
- Voxel size: 2 cm × 2 cm × 2 cm.
- The additional calculation that neutrons and photons were not transported, was done to estimate only the contribution of charged particles.

RESULTS AND DISCUSSION

1. Validation of the calculation method

- The stray charged particles outside the beam nozzle contributed to *D*, *H* and Q_D at positions over 50 cm from the field edge.
- The stray charged particles are expected to be composed of secondary protons with strong scattering power, and therefore, decrease the quality factors.

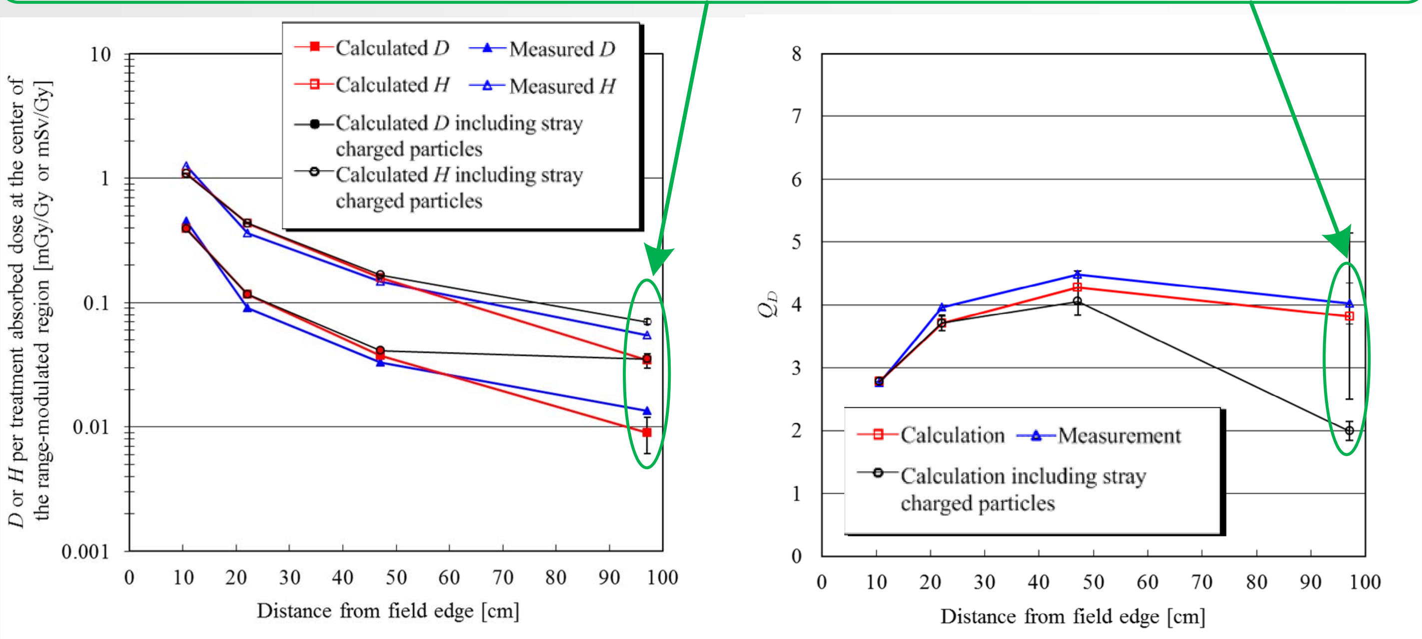


Fig. : Comparisons between calculation and measurement for the 290-Mev/u carbon beam.

- Calculations will exclude the stray charged particles from the beam nozzle from here on.
  - ✓ The measured *D* was between the calculations with and without stray charged particles, the measured Q_D agreed well with the calculation without stray charged particles, and consequently the measured *H* agreed with the calculation with stray charged particles.
  - ✓ The contribution of the stray charged particles is expected to be quite low in practice because there was equipment that could not be modeled in the calculation.
- It can be concluded that our calculation model without the stray charged particles represents the measured values **within a factor of 2**.

2. Distributions of dose equivalent in phantom at the I.C. height

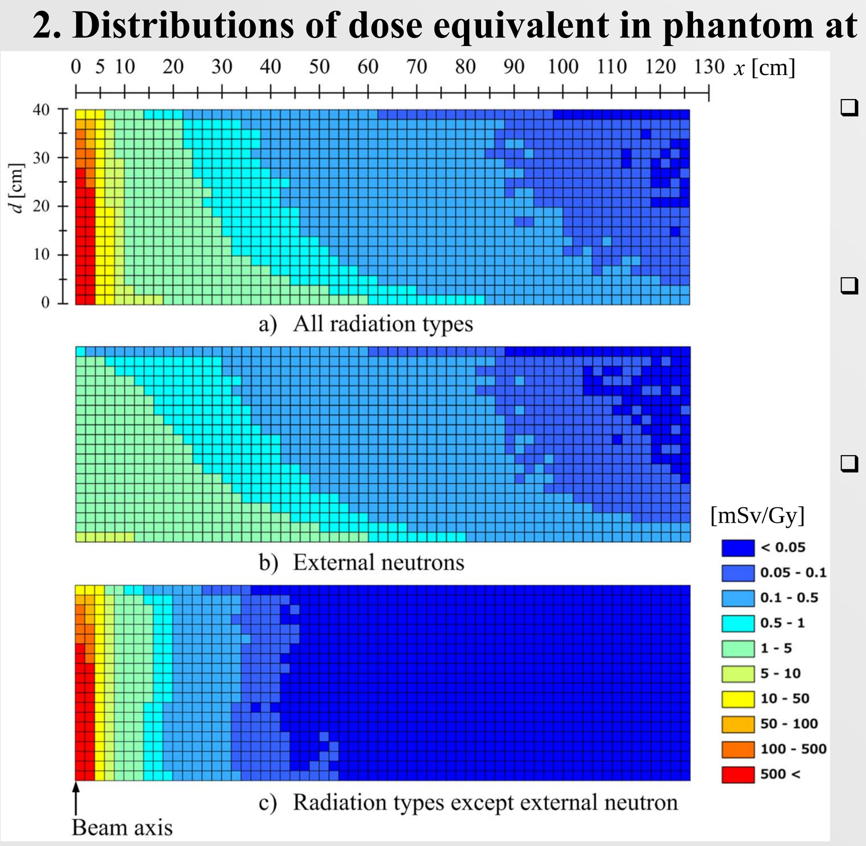
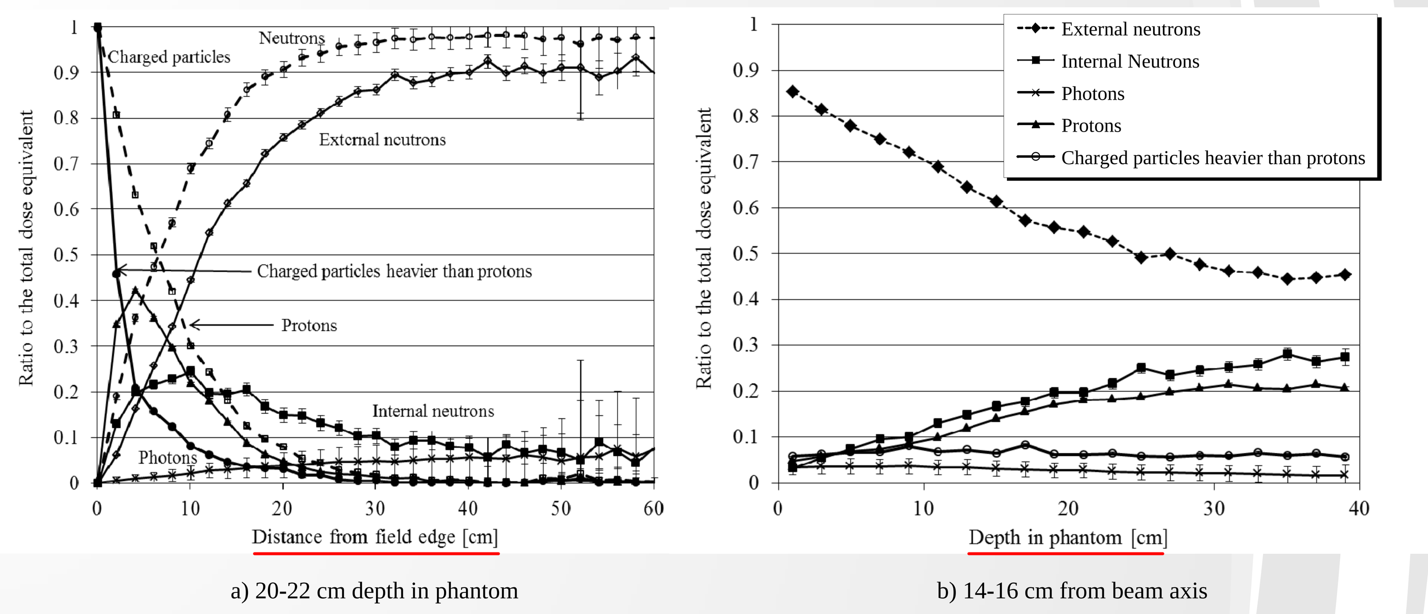


Fig. : Distributions of dose equivalent *H* in tissue-equivalent phantom for the 400-MeV/u carbon beam. (Values were normalized by the absorbed dose at the center of the range-modulated region.)

- *H* from external neutrons decreased when the position became further from the field edge and the phantom surface (*x* and *d* became larger).
- *H* from all radiation types except external neutrons decreased mainly when the position became further from the field edge (*x* became larger).
- This difference is derived from 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 pre-collimator.

3. Partial contribution of each radiation type to the total dose equivalent



a) 20-22 cm depth in phantom

b) 14-16 cm from beam axis

Fig. : Partial contribution of each radiation type to the total dose equivalent *H* for the 400-MeV/u carbon beam.

- 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 forward direction due to the direct reaction process along the beam path.

4. Passive beam vs. Active beam

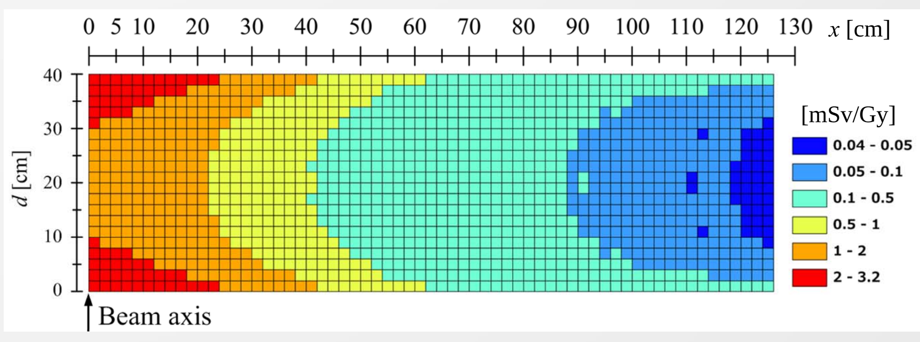


Fig.: Increase with the passive carbon beam compared to the active beam assuming two opposed equally weighted 400-MeV/u beams.

- *H* from all radiation types except external neutrons corresponds roughly to that by the active scanning beam.
- Assuming two opposed equally weighted 400-MeV/u beams, the increase with the passive carbon beam compared to the active beam reached up to **3.2 mSv/Gy**, corresponding to **78 mSv per single treatment**. (RBE: 2.36, Prescribed dose for a typical prostate cancer treatment at HIMAC: 57.6 GyE (=3.6 GyE×16 fractions))

CONCLUSIONS

- We proposed a calculation method with the PHITS code to estimate the distribution of dose equivalent in the body.
- Our calculation method:
  - ✓ can represent the measurement within a factor of 2, including not only the uncertainty of this calculation method but also those regarding the assumptions of the geometrical modeling and the PHITS code.
  - ✓ can be a powerful tool to assess the undesired dose especially outside the beam path not only in carbon-ion radiotherapy but also in proton radiotherapy regardless of the passive and active beams.

References:

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