Monte Carlo Simulation concerning Particle Therapy

Masaaki Takashina
Graduate School of Medicine, Osaka University, Osaka 565-0871, Japan

INTRODUCTION

It is well known that the particle therapy has some advantages compared with the photon therapy. For example, particle beam is effective at killing cancer cells, heavy-ion beam delivers a high dose to tumor while sparing normal tissue, etc. On the other hand, it also has some disadvantages: activation and relatively poor dosimetric precision. We are currently studying the subjects concerning the above disadvantages by Monte Carlo simulations: (A) Body activation during proton therapy, (B) Evaluation of perturbation correction factor in proton beam. We use the Monte Carlo simulation codes PHITS [1] and Geant4 [2].

(A) Body activation during proton therapy

It is a common case that, just after particle beam irradiation, medical staffs come close to patient and remove fixture etc. (about 25 second after irradiation) It has been pointed out that the patient body may be activated and the medical staff is exposed to radiation.

In the present study, we simulate the activation of patient body during proton therapy using PHITS code and decay equation, and estimate the cooling time required to protect the medical staff from radiation emitted from patient body.

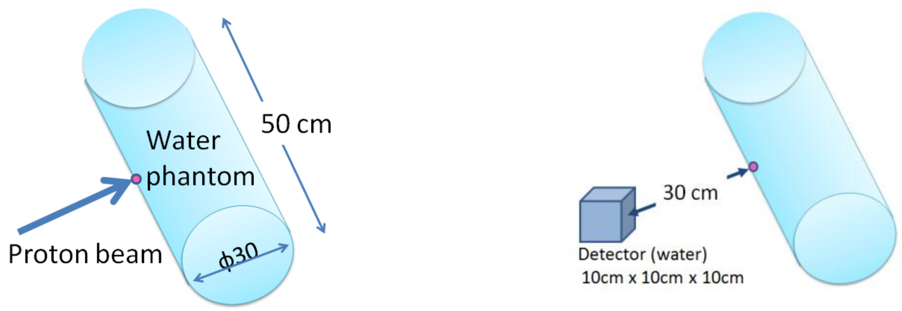


Figure 1: Geometry in the simulation calculation

We consider the water phantom having a cylindrical shape, which simulates the trunk (see left panel of Fig.1). It is assumed that the proton beam being 5 cm in diameter is irradiated on the phantom at the energy of 150 MeV with the current of 300 nA for 5 seconds. The total amount of radioactive nuclei produced in the water phantom is estimated by PHITS. Using the result of PHITS, the time dependence of activity in the phantom is calculated by solving the decay equation for each nucleus. We also evaluate the effective dose in the cubic water detector 30 cm away from the phantom (see right panel of Fig.1) by the annihilation gamma due to the radioactive nuclei using Geant4. In the present calculation, de-excitation gamma is neglected for simplicity.

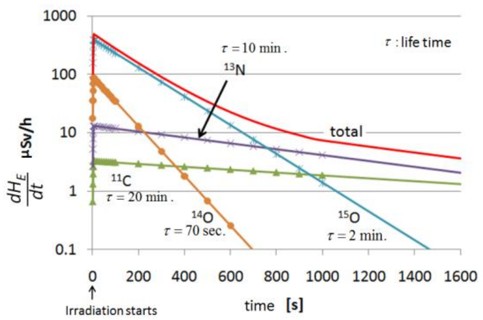


Figure 2: Time dependence of effective dose per hour.

The result of our calculation is shown in Fig.2. It is found that the activity of ^{15}O is dominant for about 10 minutes after irradiation. After that, the total activity decreases slowly. Based on this result, we also estimate the annual effective dose for medical staff with some assumption: removing fixture is started 25 second after irradiation and completed 55 second. The irradiation is performed 20 times/day and 260 days/year. The evaluated annual effective dose is 17 mSv, which is less than the limit in Japanese law (50 mSv) but higher than average (0.27-0.41 mSv) of medical staffs in Japan. To reduce the annual effective dose by half is found to require 150 second cooling time.

(B) Evaluation of perturbation correction factor in proton beam by a Monte Carlo calculation

The perturbation correction factor P_Q corrects influence from existence of wall and cavity of ionization chamber, and is needed for precise dose calibration. P_Q for photon beams (X- and gamma-rays) is well-researched. On the other hand, P_Q for particle beams is not established, and hence, it is frequently assumed to be unity. We think that precise value of P_Q is necessary for accurate dose calculation in planning of particle therapy.

In the present study, we evaluate P_Q value for particle beam using Monte Carlo simulation code Geant4. As the first step, we concentrate on the proton beam field.

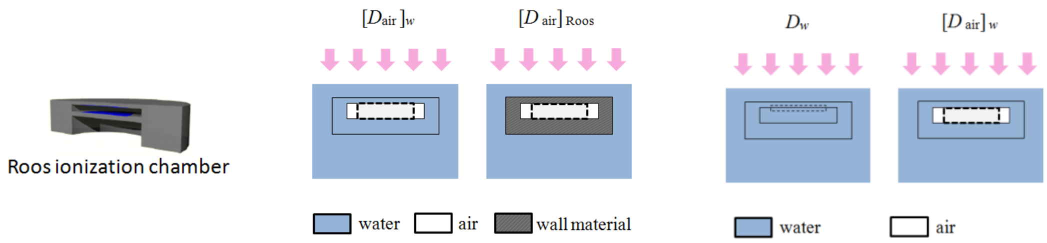


Figure 3: (Left) cross-section view of Roos ionization chamber, (middle) schematic view for the calculation of the wall correction factor, (right) same as the middle panel but for the cavity correction factor.

As ionization chamber, we consider the plane parallel type one called Roos (PTW 34001) (see left panel of Fig.3), for which the perturbation correction factor P_Q is written as a multiplication of two factors as $P_Q = P_{wall} \cdot P_{cav}$, where P_{wall} and P_{cav} are the wall and cavity correction factors, respectively. P_{wall} is calculated as $P_{wall} = [D_{air}]_w/[D_{air}]_{Roos}$, where $[D_{air}]_w$ represents absorption dose in cavity and $[D_{air}]_{Roos}$ is that in cavity surrounded by walls (see middle panel of Fig.3). P_{cav} is calculated as $P_{cav} = \frac{D_w/[D_{air}]_w}{(L/\rho)_{air}^{w}}$, where D_w represents absorption dose in water and $(L/\rho)_{air}^{w}$ is ratio of restricted collision mass stopping power between water and air (see right panel of Fig.3).

The P_{wall} and P_{cav} values are calculated at 5 cm steps up to 23 cm depth, which is shallower than the Bragg peak of the 200 MeV proton beam in water. The averaged values over the depth are $P_{wall} = 1.013$ and $P_{wall} = 1.020$. Then, we can conclude that the perturbation correction factor of ionization chamber Roos for proton beam is $P_{wall} = 1.033$.

In actual treatment, spread out Bragg peak (SOBP) is used. In order to evaluate more precise value, a sophisticated model of SOBP is necessary.

The above studies (A) and (B) have been mainly done by Masaki Suga and Michio Oda, respectively.

References

[1] K. Niita, N. Matsuda, Y. Iwamoto, H. Iwase, T. Sato, H. Nakashima, Y. Sakamoto and L. Sihver, PHITS: Particle and Heavy Ion Transport code System, Version 2.23, JAEA-Data/Code 2010-022 (2010)

[2] S. Agostinelli *et al.*, Nucl. Instr. Meth. A 506, 250 (2003)

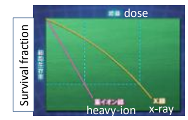
Indiana University – Osaka University

Monte Carlo simulations concerning particle therapy

Masaaki Takashina
Graduate School of Medicine, Osaka Univ.

Advantages of particle therapy compared with photon therapy

- ✓ Effective at killing cancer cells!



- ✓ Heavy-ion beam delivers a high dose to the tumor while sparing normal tissue.

Disadvantages of particle therapy compared with photon therapy

- ✓ Activation
- ✓ Precise dosimetry procedure is not established
- ✓ Precision of simulation calculation

Study with particle simulation

- ● Body activation during proton therapy
- ● Evaluation of perturbation correction factor in proton beam by a Monte Carlo calculation

Particle Simulation

Particle transport simulation code

http://geant4.cern.ch/

- ✓ Coded in C language.
- ✓ Toolkit, coded by yourself.
- ✓ High degree of freedom.
- ✓ Difficult for non-expert

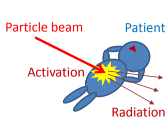
http://phits.jaea.go.jp/indexj.html

- ✓ Developed in Japan.
- ✓ Coded in Fortran.
- ✓ Good at treating **neutron transport** in low energy region.

Introduction

● Body activation during proton therapy (Suga *et al.*)

- ✓ Just after irradiation, medical staffs come close to patient, and remove fixture etc. (about 25 sec. after irradiation).
- ✓ It has been pointed out that patient body may be activated and the medical staff is exposed to radiation .



Exposed to radiation

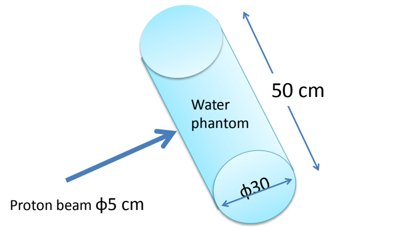
Purpose

- ✓ We simulate the activation of patient body during proton therapy by PHITS code and decay equation.
- ✓ We estimate the cooling time required to protect the medical staff from radiation emitted from patient body.

Method 1

✓ Simulation for RI production

Irradiation : Proton, 150 MeV, 300 nA , 5 sec.



The total amount of RI produced in the water phantom is estimated using **PHITS**.

Method 2

✓ Calculation of activity by solving decay equation for each nuclide obtained by PHITS calculation.

The decay equation

$$\frac{dN}{dt} = -\lambda N + \frac{\alpha I}{e} \qquad (t \leq T) \quad \cdots \text{ During irradiation}$$

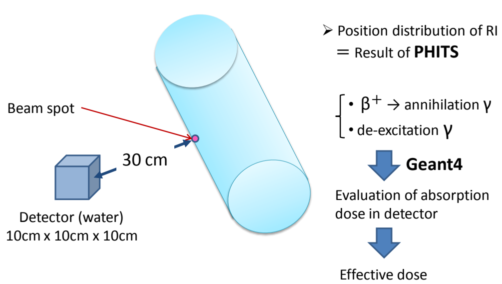
$$\frac{dN}{dt} = -\lambda N \qquad (t > T) \quad \cdots \text{ After irradiation}$$

T : stopping time of irradiation
λ : decay constant
α : production ratio for one proton
Ｉ : beam current
e : elementary charge

➢ **Time dependence of activity will be obtained.**

Method 3

✓ Calculation of effective dose



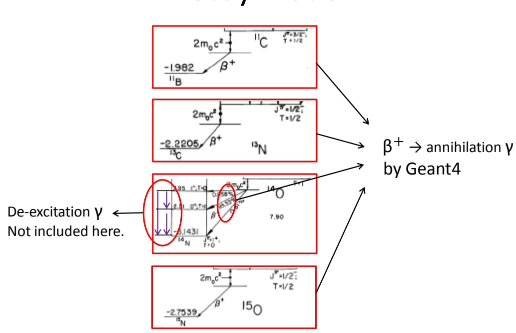
Result of PHITS

Production rate of each nucleus per incident proton.

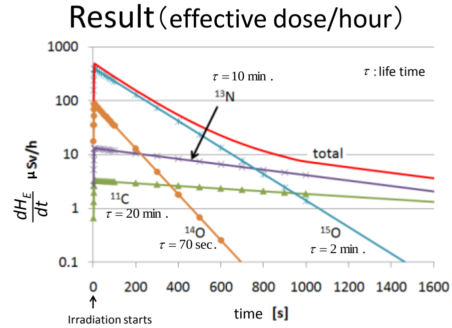
	Z \ N	5	6	7	8	9
F	9	-	-	-	1.0×10^{-6}	-
O	8	9.6×10^{-5}	3.0×10^{-3}	2.3×10^{-2}	5.3×10^{-1}	8.0×10^{-6}
N	7	1.7×10^{-4}	3.7×10^{-3}	2.4×10^{-2}	2.6×19^{-2}	1.7×10^{-4}
C	6	1.9×10^{-3}	3.2×10^{-2}	8.5×10^{-3}	3.4×19^{-3} (τ=5,700y)	6.0×10^{-6}

Stable nucleus

Decay mode

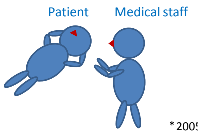


Result (effective dose/hour)



Activity of ^{15}O is dominant for 10 min. after irradiation. After that, the total activity decreases slowly.

Exposure of medical staff



- It takes 25 sec. to come close to the patient after irradiation.*
- It takes 30 sec. to remove fixture.*
  -> It takes 55 sec. to complete removal of fixture after irradiation.
- Assumed that 20 times/day and 260 days/year*

*2005 Grant-in-aid, Ministry of Health Labour and Welfare "Radiation protection in novel technology of heavy particle therapy" (in Japanese) The case of NIRS (National Institute of Radiological Science).

Effective dose for each time: $H_E = \int_{t_1}^{t_2} \frac{dH_E}{dt} dt$

$t_1 = 25[s], \quad t_2 = 55[s]$ then $H_E = 3.3[\mu Sv]$

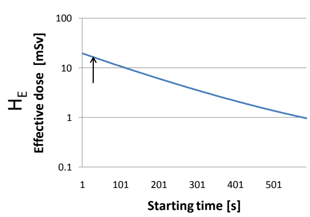
Annual effective dose: $H_E = 3.3[\mu Sv] \times 260 \times 20 = 17[mSv]$

Exposure of medical staff

(Unit mSv)	Present simulation	Limit by Japanese law	Average in Japan*
Annual effective dose	17	＜50	0.27～0.41

* Nuclear Safety Research Group, Kyoto Univ. Research Reactor Institute Resume of 106th Seminar (S. Kimura) (in Japanese) http://www.rri.kyoto-u.ac.jp/NSRG/seminar/zemi.html

Relation between starting time of removing fixture after irradiation and annual effective dose



We assume that It takes 30 sec. to remove fixture.

We take the NIRS case (starts at 25 sec.) as reference.

To reduce H_E by half → wait 150 sec.

To reduce H_E by one order → wait 450 sec. → too long!

Conclusion

for body activation during proton therapy

✓ Annual effective dose due to the body activation during proton therapy is 17 mSv.

✓ To reduce the annual effective dose by half requires two and a half minutes cooling time.

Research themes

✓ Activation

✓ Precise dosimetry procedure is not established

● Evaluation of perturbation correction factor in proton beam by a Monte Carlo calculation (Oda *et al.*)

Introduction

● Evaluation of perturbation correction factor in proton beam by a Monte Carlo calculation (Oda *et al.*)

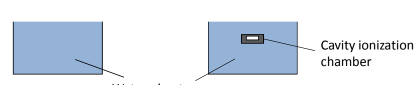
- *Perturbation correction factor* : P_Q
  - Needed for dose calibration

    $D_{w,Q} = M_Q \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0}$

    $$k_{Q,Q_0} = \frac{[W_{air} \cdot (L/\rho)^{w}_{air} P_Q]_Q}{[W_{air} \cdot (L/\rho)^{w}_{air} P_Q]_{Q_0}}$$

    k_{Q,Q_0} : beam quality conversion factor

    Q : radiation quality (線質)
  - Corrects influence of existence of wall and cavity



Introduction

- The correction factor for particle beam is not established
- P_Q is frequently assumed to be 1.0

IAEA , TECHNICAL REPORTS SERIES No. 398V.11b, 2004

- Precise value is needed for accurate dose calculation

Purpose of this study

We evaluate the perturbation correction factor P_Q for particle beam using Monte Carlo simulation code Geant4.

In the present study, we concentrate on the proton beam field.

Method

For plane parallel ionization chamber Roos (PTW 34001)

$P_Q = P_{wall} \cdot P_{cav}$ in the case of plane parallel type

perturbation by cavity

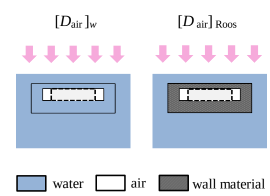
perturbation by wall

Roos ionization chamber

Method

Calculation of P_{wall} (wall correction factor)

$P_{wall} = [D_{air}]_w / [D_{air}]_{Roos}$



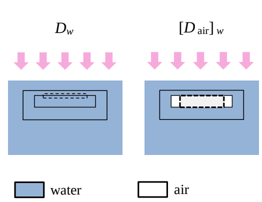
$[D_{air}]_w$: Absorption dose in cavity

$[D_{air}]_{Roos}$: Absorption dose in cavity surrounded by walls

Method

Calculation of P_{cav} (cavity correction factor)

$$P_{cav} = \frac{D_w / [D_{air}]_w}{(L/\rho)^w_{air}}$$



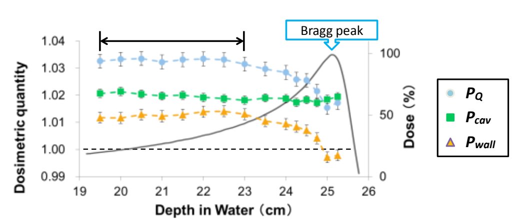
D_w : Absorption dose in water

$[D_{air}]_w$: Absorption dose in cavity

$(L/\rho)^w_{air}$:ratio of restricted collision mass stopping power between water and air

Result for proton beam

200 MeV pencil beam



・averaged value（～23cm depth）

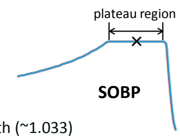
P_{wall}	P_{cav}	P_Q
1.013	1.020	1.033

Result for proton beam

- Actual treatment uses spread out Bragg peak (SOBP)
  - Using **preliminary** SOBP beam model

P_{wall} = 1.012
P_{cav} = 1.021
→ P_Q = 1.033

Calculated at central point of plateau region



  - almost equivalent to those up to 23 cm depth (~1.033)

The present result implies that P_Q in plateau region of SOBP is 1.033.

Conclusion

for "Evaluation of perturbation correction factor in proton beam by a Monte Carlo calculation"

✓ P_Q = 1.033 for proton beam field

✓ 3% is large error in treatment planning of radiation therapy.

Is this result true?

Further investigation is needed!

Collaboration with IU group

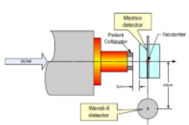
● Secondary neutron dose during proton therapy

✓ Exp. by MPRI (Indiana U.) group

D. Hecksel et al., Med. Phys. 37 (2010) 2910.

✓ in double scattering method

✓ in scanning method



Simulation study by PHITS

Thank you for your attention