Table 1 Activities, required times and distances from the radiation source for a radiation technologist working in a carbon ion radiotherapy facility. The evaluation of the effective dose uses the dose rate by gamma rays and the evaluation of the equivalent dose to the skin uses the total dose rate by the beta and gamma rays.

Activity*	Time from beam stop to activity start	Time needed for the work	Source to evaluation point distance					
			Effective dose evaluation			Equivalent dose of skin evaluation		
			MLC	Collimator	Amends filter	MLC	Collimator	Amends filter
a	25 s	30 s	50 cm	30 cm	30 cm	50 cm	30 cm	30 cm
b	55 s	10 s	50 cm	30 cm	30 cm	1.5 cm	0 cm	0 cm
c	1 min 05 s	10 s	50 cm	30 cm	30 cm	1.5 cm	30 cm	0 cm
d	1 min 15 s	15 s	—**	—**	30 cm	—**	—**	0 cm
e	1 min 30 s	10 s	—**	30 cm	—**	—**	0 cm	—**

Notes: * Activity: a, detaching the patient fastening device; b, detaching the patient collimator (putting it on a side table); c, detaching the amends filter (putting it on a side table); d, storing the amends filter (moving it to a depository); and e, storing the patient collimator (moving it to a depository).
** Because the distance is long, the dose contribution is ignored.

tient compensator (denoted as the bolus) were also derived, and the summation of these three integrated values resulted in the effective dose from the process of detaching the patient-fixation device.

The effective doses were also estimated from other processes such as detaching the patient collimator and the patient compensator and putting them onto a nearby table, and storing them on a shelf. The sum of those values was considered to be the maximum of the effective dose received by the radiation technologist in one therapeutic irradiation.

Measurements were done at four facilities: Proton Medical Research Center (PMRC) at Tsukuba University; Shizuoka Cancer Center (SCC); HIMAC of the National Institute of Radiological Sciences (NIRS); and Hyogo Ion Beam Medical Center (HIBMC). Measurements were made at the HIBMC for both a carbon ion radiotherapy facility and a proton radiotherapy facility.

4.2.6.1. Estimation of exposure dose at a carbon ion radiotherapy facility (NIRS)

NIRS is used to carry out daily therapeutic irradiations using several teams. Each team consists of two radiation technologists and one nurse. The radiation technologists are responsible for all the processes listed in Table 1. It is assumed that all the processes are done by one radiation technologist in order to assess the possible maximum extent of effective dose, though in actual treatments the processes are shared by the two radiation technologists. The times needed for the processes and distances from the radiation source are also listed in the table. In Table 1, to estimate a maximum dose, we refer to the shortest time from beam stop to activity start, and, the longest example as for the times needed for the processes. The annual effective dose was estimated based on Table 1 with the assumption that the radiation technologist repeats the sequential process 20 times a day and 260 days a year (65 days in 3 months).

4.2.6.2. Estimation of exposure dose at proton radiotherapy facilities

The same conditions and assumptions as in 4.2.6.1 were used for the three proton therapy facilities and the extent of effective dose and skin surface dose were estimated for them.

4.2.6.3. Results and discussions on the exposure dose to radiation technologists

Tables 2 and 3 summarize the estimated doses received by one radiation technologist who was assumed to carry out all tasks alone at a carbon ion radiotherapy facility (HIMAC, HIBMC) and a proton facility (HIBMC, PMRC, SCC), respectively. The Japanese Government regulates the effective dose limits as 20 mSv/year for male workers (as a 5-year average) or 5 mSv/3 months for female workers, and both male and female workers have an allowed equivalent dose to the skin of 500 mSv/year. The estimated effective dose and equivalent dose to the skin to be received by a radiation technologist were compared with these regulations.

In the case of carbon ion radiotherapy with 290 MeV/n, the estimated doses at HIMAC corresponded to 5.3% (1.057/20=0.053) and 1.9% (9.701/500=0.019) of the regulated annual limits of effective dose and equivalent dose to the skin, respectively. 400 MeV/n resulted in 3.3% (0.665/20=0.033) and 0.8% (4.132/500=0.0083) for effective dose and equivalent dose to the skin, respectively. At HIBMC, the effective dose was 2.7% (0.530/20=0.0265) whereas it was 1.1% (5.410/500=0.01082) for equivalent dose to the skin.

In contrast, the results from proton therapy facilities were higher: 15.2% (3.040/20=

Table 2 Evaluation of effective dose and equivalent dose of skin for a radiation technologist working in a carbon ion radiotherapy facility

Activity	Effective dose (μSv)			Equivalent dose of skin (μSv)		
	HIMAC*	HIMAC**	HIBMC	HIMAC*	HIMAC**	HIBMC
a	0.108	0.085	0.054	0.119	0.125	0.099
b	0.034	0.018	0.017	0.759	0.252	0.417
c	0.034	0.017	0.017	0.331	0.226	0.136
d	0.005	0.007	0.006	0.299	0.192	0.111
e	0.023	—	0.007	0.358	—	0.277
Total dose (μSv)	0.203	0.128	0.101	1.866	0.795	1.040
Annual exposure (mSv)	1.057	0.665	0.530	9.701	4.132	5.410
Total exposure for 3 months (mSv)	0.264	0.166	0.133	—	—	—

Notes: * 290 MeV/n carbon ion irradiation of about 150 mm underwater range.
** 400 MeV/n carbon ion irradiation of about 250 mm underwater range.

Table 3 Evaluation of effective dose and equivalent dose of skin for a radiation technologist working in a proton radiotherapy facility

Activity	Effective dose (μSv)			Equivalent dose of skin (μSv)		
	HIBMC	PMRC	SCC	HIBMC	PMRC	SCC
a	0.294	0.205	0.496	0.538	0.431	1.138
b	0.096	0.066	0.157	2.918	2.309	5.002
c	0.095	0.065	0.153	0.940	1.042	2.284
d	0.049	0.016	0.078	1.071	0.928	3.030
e	0.051	0.086	0.180	1.982	1.289	2.673
Total dose (μSv)	0.585	0.438	1.064	7.449	5.999	14.127
Annual exposure (mSv)	3.040	2.276	5.531	38.742	31.196	73.459
Total exposure for 3 months (mSv)	0.760	0.569	1.383	—	—	—

0.152) for effective dose and 7.7% (38.742/500=0.077484) for equivalent dose to the skin at HIBMC. The values were 11.4% (2.276/20=0.1138) for effective dose and 6.2% (31.196/500=0.062) for equivalent dose to the skin at PMRC, and at SCC, the values were 27.7% (5.531/20=0.2765) for effective dose and 14.7% (73.459/500=0.1469) for equivalent dose to the skin, respectively.

It should be noted here that in the case of X-ray radiotherapy, the annual effective dose received by a radiation technologist is considered to be negligible if the accelerated energy of the medical electron linear accelerator is lower than 10 MeV while it is significant for energies above 10 MeV. The dose has been reported, for example, by Almen et al.[1] and Perrin et al.[2] in Table 4.

These results suggested that the extent of annual effective dose received by a radiation technologist is comparable between charged particle radiotherapy and high-energy X-ray radiotherapy (higher than 10 MeV) using a linear accelerator. From this viewpoint, we concluded that though the current regulations on dose received by a radiation worker were targeted only for X-ray radiotherapy, they are also applicable for the new modality—charged particle radiotherapy.

4.2.6.4. Exposure of patient's family members and effects on the environment

Here we discuss the irradiation experiment with the Tough Water Phantom (Kyoto Kagaku Co., Ltd., Kyoto, Japan).

For evaluation of exposure of patient's family members, the following scenario was assumed. A patient leaves the treatment room 2 min after the end of the irradiation and a member of his/her family attends him/her for 2 h. The dose of the member was estimated by integrating Eq. (2) for the gamma-ray dose rate at 30 cm from the surface of the Tough Water Phantom from t_1=2 min through t_2=120 min. The charged particle treatment for a patient would be done for 20 to 30 irradiations at most. The total exposure was obtained

Table 4 Trial of the annual effective dose calculation for medical workers

Author	Accelerator energy	Body	Skin surface
Almen et al. (1991)	13–17 MeV	1.0–2.8 mGy	0.7–3.3 mGy
Perrin et al. (2003)	18 MeV*	2.5 mSv	

on the safe side by multiplying the integrated value of Eq. (2) by 30. In the case of carbon ion treatment, the exposure of the family member was calculated as 23.5 μSv for HIMAC and 20.8 μSv for HIBMC. The exposure was 128.9 μSv in the case of proton treatment at HIBMC.

Most radioactive nuclides produced by a charged particle treatment have very short half lives (as shown at graphs in the Appendix). Even if the time the family member attends to the patient is prolonged more than 2 h, the exposure has hardly any increase. Therefore we concluded that the exposure of a patient's family member is sufficiently lower than the public dose limit of 1 mSv/y.

4.3. *Radioactive concentrations of the treatment room air and the exhaust from facilities and the waste water*

4.3.1. *Air activation with particle radiotherapy*

The air activation during beam acceleration and transport falls under the Law Concerning Prevention of Radiation Hazards; here we considered the air activation only in the treatment room.

Charged particle radiotherapy has been carried out for more than 30 years, and the nuclei, energies and intensities which are presently used will not be significantly changed in the near future. Therefore we assumed the following particles and energies for the estimation of air activation.

Nuclei: protons and ^{12}C
Energy: 250 MeV for p, and 400 MeV/n for ^{12}C

In the treatment room, the incident beam is extracted into the air for irradiation and absorbed into beam collimators, a patient body or phantom, which produces secondary neutrons. The air activation is therefore induced by incident charged particles and secondary neutrons.

4.3.1.1. *Air activation by charged particles*

If we assumed a uniform D Gy dose (absorbed dose to water) over volume, V_{tr}, the total absorbed energy of the volume, E_{tr}, was given by Eq. (3).

$$E_{tr} = V_{tr} \times D \times 10^{-3} \quad \text{(J)} \qquad (3)$$

The number of particles, N, was roughly obtained by Eq. (4).

$$N = \frac{E_{tr}}{E \times 1.6 \times 10^{-13}} \quad \text{(particles)} \qquad (4)$$

where E (MeV) is the total energy of the particle. The number of protons is about 20 times larger than that of ^{12}C according to eq. (4). The activation cross section of ^{12}C is thought to be about 2 times larger than that of a proton.(Note 1) Hence the radioactivity induced

(Note 1) This is roughly estimated from the geometric cross section σ_g
$\sigma_g = \pi r_0^2 (A_p^{1/3} + A_T^{1/3})^2$,
where r_0 is 1.07×10^{-13} cm, A_p and A_T are projectile and target mass numbers, respectively.
More detailed information on σ_g is given in Ref. 4.

by protons is expected to be about 10 times stronger, and so here we estimated the case for proton therapy.

Air is mainly activated by the interaction of the primary beam. Radionuclide being produced are ^{15}O, ^{13}N, ^{11}C, ^{7}Be and ^{3}H. The activation cross sections of air colliding with hadrons are quoted from Sullivan[3)] and listed in Table 5.

If the therapeutic particles pass through the air of 1.5 m, the induced radioactivity A_0 (Bq) is calculated by the following expression with the air cross section Σ (cm^{-1}) of Table 5 and the decay constant λ (s^{-1}).

$$A_0 = \lambda \sigma N \times 150 \quad (Bq) \qquad (5)$$

Estimating the radioactive concentration of room air and exhaust on the safe side, we assumed that all the licensed particles for a day were irradiated at once and the concentration dropped because of radioactive decay and operation of the ventilation system. When the volume of the treatment room is V (cm^3), ventilation speed of the room is v ($cm^3\,s^{-1}$), and ventilation speed of the whole facility is v_T ($cm^3 \cdot s^{-1}$), then the air concentrations of the treatment room, C_R ($Bq\,cm^{-3}$), and the exhaust, C_X ($Bq\,cm^{-3}$), averaged over the time T (s) are calculated by Eqs. (6) and (7).

$$C_R = \frac{A_0}{VT(\lambda + v/V)}[1 - e^{-(\lambda + v/V)T}] \qquad (6)$$

$$C_X = \frac{vA_0}{v_T VT(\lambda + v/V)}[1 - e^{-(\lambda + v/V)T}] \qquad (7)$$

These values were obtained for the two operating facilities. In the case of National Cancer Center Hospital East (NCCHE), T is 24 (h),(Note 2) volume of the treatment room with a rotating gantry V is 228 (m^3), ventilation speed of air in the room v is 1000 ($m^3\,h^{-1}$), and that of the whole facility v_T is 46000 ($m^3\,h^{-1}$). The

Table 5 Activation cross sections of air colliding with hadrons

Nuclide	Half life	Reaction	Cross section (mb)	Air cross section (cm^{-1})*
^{3}H	12.33y	$^{16}O(x, sp)^{3}H$	30	1.4×10^{-6}
		$^{14}N(x, sp)^{3}H$	30	
^{7}Be	53.29d	$^{16}O(x, sp)^{7}Be$	5	4.4×10^{-7}
		$^{14}N(x, sp)^{7}Be$	10	
^{11}C	20.39m	$^{16}O(x, sp)^{11}C$	5	4.4×10^{-7}
		$^{14}N(x, sp)^{11}C$	10	
^{13}N	9.965m	$^{16}O(x, sp)^{13}N$	9	4.9×10^{-7}
		$^{14}N(x, sp)^{13}N$	10	
^{15}O	2.037m	$^{16}O(x, sp)^{15}O$	40	4.2×10^{-7}

Note: * Atomic densities: N, $3.91\times10^{19}\,cm^{-3}$; O, $1.05\times10^{19}\,cm^{-3}$; ^{40}Ar, $2.32\times10^{17}\,cm^{-3}$.

(Note 2) The air conditioning system is continuously operating for 24 hours at all facilities in Japan except for the Wakasa wan energy research center where the operating time is 16.5 hours.

results are shown in Table 6. The exhaust concentration includes the contributions of all the treatment rooms. In the regulation law, the radioactivity concentration limits in the treatment room air and the exhaust from the facility shall be given as the average values over one week and three months, respectively, however, here in this estimation, the average values over 24 hours are given on the safe side.

Table 6 indicates that the concentrations of the treatment room air and the exhaust were below the legal limits. In the case of the SCC, the summed ratios of the room air and the exhaust concentrations to the limits were 8.0×10^{-3} and 3.3×10^{-1}, respectively, and they were also below the legal limits.

The values of NCCHE and SCC shown here were the cases when the irradiations were done at the licensed limits which were decided considering occasional dose measurements. Daily irradiations are usually done far below the licensed limit, and the concentrations are also much lower than the above.

4.3.1.2. Air activation by secondary neutrons

4.3.1.2.1. Air activation by fast neutrons

The air activation by fast neutrons is calculated similarly as that by charged particles in Eq. (5). The induced radioactivity A_0 is given by

$$A_0=\lambda\sigma N_n\times l_N \tag{8}$$

where l_N is effective flight path of fast neutrons in the room, N_n is the number of neutrons above threshold energy (about 20 MeV) of nuclear reactions in Table 5 and given as

$$N_n=N\times R_n \tag{9}$$

where R_n is the number of neutrons above threshold energy of 20 MeV per incident projectile. The air cross section σ of Table 5 can be applied also for neutron-induced reactions.

l_N is the distance from the neutron production point to floor, wall and ceiling in the treatment room. If we assumed that the room is shaped a sphere with a volume, V and that neutrons are produced at the center of the room, $l_N=\{3V/(4\pi)\}^{1/3}$ is obtained. The A_0 values for fast neutrons in Eq. (8) are given by multiplying the A_0 values for charged particles in Eq. (5) with $(l_N/150)\cdot R_n$. The R_n values for

Table 6 Radioactivity concentrations of the treatment room air, C_R, and the exhaust, C_X, their legal concentration limits, L_R and L_X, and the ratios of the concentrations to their limits in the case of NCCHE.

Nuclide	A_0 (Bq)	C_R (Bq/cm³)	L_R (Bq/cm³)	C_R/L_R	C_X (Bq/cm³)	L_X (Bq/cm³)	C_X/L_X
^3H	7.1×10^1	3.0×10^{-9}	0.5	5.9×10^{-9}	1.3×10^{-10}	3×10^{-3}	4.4×10^{-8}
^7Be	1.9×10^3	7.8×10^{-8}	0.5	1.6×10^{-7}	3.5×10^{-9}	2×10^{-3}	1.8×10^{-6}
^{11}C	7.1×10^6	2.0×10^{-4}	0.2	1.0×10^{-3}	9.0×10^{-6}	7×10^{-4}	1.3×10^{-2}
^{13}N	1.6×10^7	3.4×10^{-4}	0.2	1.7×10^{-3}	1.5×10^{-5}	7×10^{-4}	2.2×10^{-2}
^{15}O	6.8×10^7	5.0×10^{-5}	0.2	2.5×10^{-3}	2.2×10^{-5}	7×10^{-4}	3.2×10^{-2}
			Total	5.2×10^{-3}			6.7×10^{-2}

neutrons above 5 MeV are used in place of those above 20 MeV on the safe side[5,6]. The thus-obtained R_n values are 0.25 for iron injected by 250 MeV proton beam and 4.4 for copper injected by 400 MeV/n ^{12}C beam.[Note 3]

If l_N is assumed to be 500 cm on the safe side, the radioactivity by proton-induced neutrons is 0.83 times of that by proton beam itself and the sum is 1.83 times of that by proton beam itself. While the radioactivity by carbon-induced neutrons is 14.7 times of that by proton beam itself and the activation cross section of ^{12}C is about 2 times higher than that of proton, therefore the sum is 16.7 times of that by proton beam itself. As mentioned above, it is required for the treatment that the number of protons is about 20 times larger than that of ^{12}C. The radioactivity by carbon beam and carbon-induced neturons is 45.6% (=(16.7/20)/(1×1.83)×100) of that by proton beam and proton-induced neutrons This indicates that proton beam still induces higher radioactivity than carbon beam.

4.3.1.2.2 Air activation by thermal neutrons

The dominant component from air activation caused by thermal neutrons is the $^{40}Ar(n,\gamma)^{41}Ar$ reaction which has a cross section of 660 (mb). Thermal neutron flux in the treatment room Φ_{th} ($cm^{-2}\,s^{-1}$) could be estimated by Eq. (10)[4]:

$$\Phi_{th} = C \cdot \frac{Q}{S} \quad (cm^{-2}\,s^{-1}) \qquad (10)$$

where C is a constant (=4)[7], Q is the neutron yield in the room (=0.3 $proton^{-1}$)[8], and S is the surface area of the room, including walls, a roof and a floor (cm^2).

The produced radioactivity A_0 (Bq) was calculated by the following formula with the air cross section Σ (cm^{-1}), decay constant of ^{41}Ar, and the volume of the room V (cm^3).

$$A_0 = \lambda \Sigma \Phi_{th} V \quad (Bq) \qquad (11)$$

The air concentrations of the room and exhaust were calculated by Eqs. (6) and (7).

In the case of NCCHE the summed ratios of the room air and the exhaust concentrations to the limits were 7.4×10^{-5} and 6.6×10^{-3}, respectively, and those of SCC were 5.1×10^{-7} and 5.4×10^{-3}. These values were less than a tenth of the results of the primary beam described in Sec. 4.3.1 and the total air activation including ^{41}Ar production was below the legal limit.

The ^{41}Ar production by carbon beam is equal to or lower than that by proton considering the number of secondary neutrons and the number of incident particles required for the treatment as mentioned above.

4.3.1.3 Summary of air activation

Radioactivity concentrations of the treatment room air, C_R, and the exhaust, C_X, their legal concentration limits, L_R and L_X, and the ratios of the concentrations to their limits for all particles are shown in the case of NCCHE in Table 7. The sums of the ratios are less than 0.11. This result showed that the air activation is much lower than the Japanese legal concentration limit.

This investigation was performed for the facilities in operation. However, the radioactive concentrations of the treatment room air depend strongly on the volume, the ventilation

(Note 3) The beam efficiency is generally less than 30 % in the passive charged-particle radiotherapy. Because more than 70 % of particles stop in the beam line devices, it is reasonable that iron or copper is assumed as the neutron-producing material.

speed and the time of the treatment room. The radioactive concentrations of exhaust also depend on the ventilation speed of the facility, because the treatment room generally shares the exhaust outlet with other rooms such as an accelerator room. These should be fully taken into consideration as the new particle radiotherapy facility is designed and constructed.

4.3.2. Waste water concentration of treatment facilities

Radioactivity of a treated patient can be transferred to the waste water of the facility through urine. Specific radioactivity(Note 4) of a patient 5 min after a carbon beam irradiation at HIMAC was about 80 ($Bq\,g^{-1}$). Since the half life of the activity was 13 min, it was thought to be a mixture of ^{11}C and ^{13}N for which half lives were 20 min and 10 min, respectively. In the case of the HIBMC the specific radioactivity at 5 min after the irradiation was estimated to be 323 ($Bq\,g^{-1}$) for proton radiotherapy and 45 ($Bq\,g^{-1}$) for carbon ion radiotherapy. ^{11}C has a longer half life and is more hazardous than ^{13}N, and if all the activity was assumed to be ^{11}C for which the waste water concentration limit is 40 ($Bq\,g^{-1}$), the specific radioactivity of the patient would be 1 to 2 times higher than the limit for carbon therapy and 8 times higher for proton therapy. Since urine is firstly diluted by toilet water several tenfold, and then it is diluted further by the waste water from the whole hospital, the influence to the environment is negligibly small, and no legal regulations seem to be necessary.

Table 7 Radioactivity concentrations of the treatment room air, C_R, and the exhaust, C_X, their legal concentration limits, L_R and L_X, and the ratios of the concentrations to their limits for all

Nuclide	A_0 (Bq)	C_R (Bq/cm³)	L_R (Bq/cm³)	C_R/L_R	C_X (Bq/cm³)	L_X (Bq/cm³)	C_X/L_X
^{3}H	8.8×10^{1}	4.8×10^{-9}	0.5	9.6×10^{-9}	2.2×10^{-10}	3×10^{-3}	7.2×10^{-8}
^{7}Be	2.4×10^{3}	1.3×10^{-7}	0.5	2.6×10^{-7}	5.7×10^{-9}	2×10^{-3}	2.9×10^{-6}
^{11}C	8.8×10^{6}	3.3×10^{-4}	0.2	1.6×10^{-3}	1.5×10^{-6}	7×10^{-4}	2.1×10^{-2}
^{13}N	2.0×10^{7}	5.6×10^{-4}	0.2	2.8×10^{-3}	2.5×10^{-5}	7×10^{-4}	3.6×10^{-2}
^{15}O	8.5×10^{7}	8.1×10^{-4}	0.2	4.1×10^{-3}	3.6×10^{-5}	7×10^{-4}	5.2×10^{-2}
^{41}Ar	1.9×10^{6}	7.4×10^{-5}	0.1	7.4×10^{-4}	1.6×10^{-6}	5×10^{-4}	3.2×10^{-3}
			Total	9.2×10^{-3}			1.1×10^{-1}

(Note 4) The effective dose at 30 cm from the irradiated surface was calculated with the EGS4 code[9] that the average dose was 7.7×10^{-17} Sv when a 0.511 MeV gamma ray was emitted at an arbitrary point in the irradiated water volume of 10 cm by 10 cm by 25 cm depth.
In the case of a carbon irradiation at HIMAC the dose rate at 30 cm from the surface of the Tough Water Phantom at 5 min after the end of irradiation was 2.1 μSv/h, and the radioactivity (A) of β^+ emitters in the irradiated volume was obtained by the following expression.
$A=2.1\times10^{-6}/(7.7\times10^{-17}\times2\times3600)=3.8\times10^{6}$ (Bq)
If it is assumed that the weight of the patient is 50 kg, the specific activity is 76 Bq/g.

4.4. Measurement of neutron ambient dose equivalent in passive carbon ion and proton radiotherapies

In particle radiotherapy, undesired radiation exposure in normal tissues around a treatment target is less than that in conventional radiotherapy because of the physical property known as the Bragg peak. In addition, carbon ion beams can reduce the undesired exposure laterally as they have less scattering power than protons. The reduction of such undesired exposure is an important consideration in treatment planning. However, undesired radiation exposure in normal tissues far from the treatment target cannot be considered in the treatment planning, because it is caused by secondary radiation as well as leakage and scattered primary particles. Though this exposure is considerably lower than that near the treatment target, it cannot be neglected in estimating the risk for secondary cancer especially for younger patients. It is particularly important to investigate secondary neutrons which are inevitably produced within the patient and beam line devices in particle radiotherapy due to the potency of their biological effect.

Recent studies on the secondary neutrons in passive proton radiotherapy have been done, and the neutron dose equivalents were evaluated by experiments and Monte Carlo simulations[10)–14)]. However, these results varied by a factor of 100. The reasons for this difference include the following effects (1) parameter settings of beam-shaping devices, e.g. a spread-out Bragg peak (SOBP) width, incident proton energy and field size; and (2) the experimental/calculation setup, e.g. the size and material of the phantom, etc.

One point of this study was to compare the secondary neutron doses in carbon ion and proton radiotherapies. Another was to provide basic data to determine regulations for secondary neutron exposure in particle radiotherapy by investigating the differences in secondary neutron exposure at several facilities. Since the measurement and calculation methods and associated results of the secondary neutron dose in previously published papers largely differ as mentioned above, we measured such doses at two carbon ion radiotherapy facilities and four proton radiotherapy facilities in Japan; we tried to have approximately the same parameter settings for the beam-shaping devices and exactly the same experimental setup. This procedure would determine the difference among beam lines that may depend on their materials and the locations of the beam line devices, and the methods for making a laterally-uniform irradiation field.

4.4.1. Materials and methods

The experiments were performed at NIRS, HIBMC, NCCHE, SCC and PMRC.

Table 8 shows the major properties of the beam lines. Neutron ambient dose equivalents per treatment absorbed dose were measured using a rem meter, WENDI-II[15)]. This rem meter has a response extended to 5 GeV neutrons, and was developed at Los Alamos National Laboratory. Figure 1 shows a photograph and a schematic view of the experimental setup at SCC. A water phantom (external size: 22×24×39 cm^3) was placed to simulate the patient at the isocenter as the center of the phantom coincided with the isocenter. The center of the WENDI-II was set to be as high as the isocenter. The measured position represented by the distance between the center of

Table 8 Major properties of the beam lines

Facility	Beam species*	Maximum beam energy in the radiotherapy** [MeV/n]	Method for making a laterally-uniform irradiation field¶	Pre-collimator¶¶	Final collimator*¶
NIRS	C	400	W	FLC (Aluminum)	MLC (Iron)/ PC (Brass)
HIBMC	C/p	320(C), 210(p)	W	2 RCs (Aluminum)	MLC (Iron)/ PC (Brass)
SCC	p	220	W	2 RCs (Aluminum)	MLC (Iron)/ PC (Brass)
NCCHE	p	235	D	RC (Brass), FLC(Brass)	PC (Brass)
PMRC	p	250	D	RC(Copper), MLC (Brass)	PC (Brass)

Notes * C, carbon ions; p, protons.
** This means the energy extracted from an accelerator, not that entering a patient after energy losses within the beam line devices.
¶ W, single-ring wobbling method; D, double scattering method.
¶¶ RC, ring collimator; FLC, four-leaf collimator.
*¶ MLC, multi-leaf collimator; PC, patient collimator.

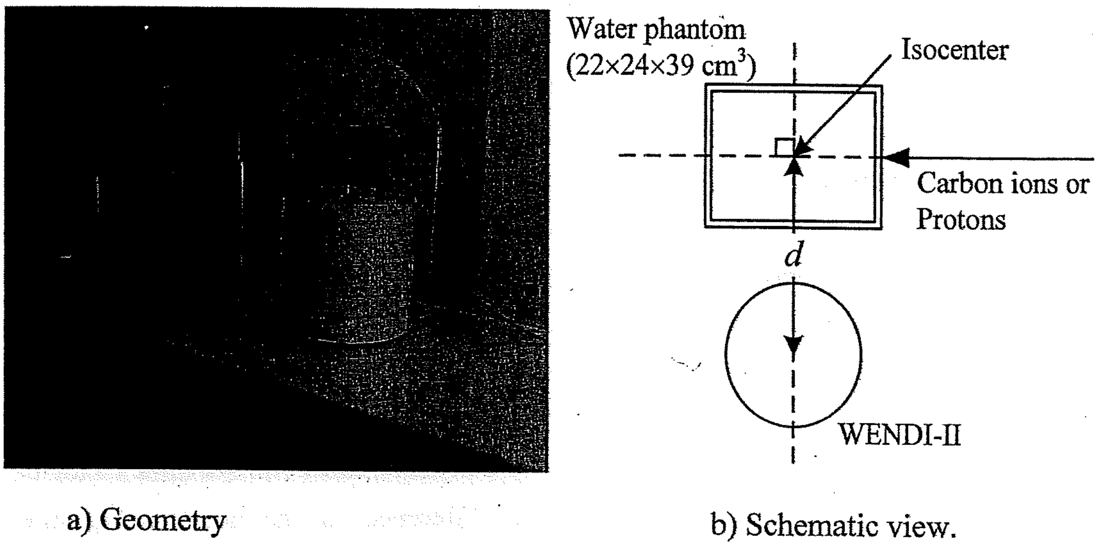


Fig. 1 Experimental setup at SCC[16]

the WENDI-II and the isocenter, *d*, was varied from 50 to 200 cm. Table 9 shows the beam line parameters used. Since the secondary neutrons increase as the incident particle energy increases, it is necessary to investigate the neutron dose for the maximum beam energy at each beam line. The maximum values of beam energy in radiotherapies were used for the calculation, and the energy close to 160 MeV for the proton beam. The 160 MeV proton beam was selected to be comparable with settings in published papers. Another energy chosen was

Table 9 Beam line parameters used in this study

Facility	Beam energy [MeV/n]	Type of beam line*	Diameter of laterally-uniform irradiation field, D_{irr} [mm]	SOBP Width, W_s [mm]	Aperture size of the adjustable pre-collimator [mm^2]	Distance between the final collimator and the isocenter, D [mm]	Aperture size of the final collimator [mm^2]
NIRS	400, 290	H	100, [200]**	60, [120]	78.1×70 (FLC)	500, [700]	58.1×50 (MLC)
HIBMC	320 (C), 210 (p), 150 (p)	H	160	60	—	400	52.5×50 (MLC)
SCC	220, 160	G	190	60	—	400	52.5×50 (MLC)
NCCHE	235, 150	G	283	60, [100]	90×90 (FLC)	300, [500]	50×50 (PC)
PMRC	250, 155	G	200	60	110.2×100 (MLC)	300	50×50 (PC)

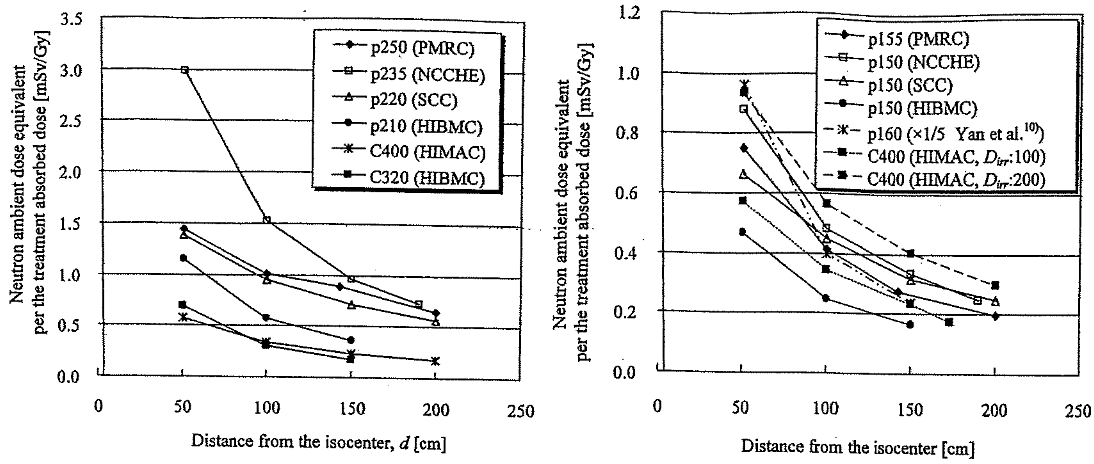
Notes: * H, fixed horizontal line; G: gantry line; other abbreviations are as given in Table 8.
** Square brackets indicate a parameter for which the contribution was investigated.

that used for large-field irradiation in the horizontal beam line at NIRS of 290 MeV/n. The standard beam line parameters were for the irradiation field of 50 mm×50 mm determined by the final collimator and the SOBP width of 60 mm. Measurements with different beam line parameters were also performed at NIRS and NCCHE to investigate their contribution.

4.4.2. *Results*

Figure 2 shows the measured neutron ambient dose equivalents per treatment absorbed dose at the center of the SOBP. Figure 3 illustrates neutron ambient dose equivalents with different setting parameters for the beam-shaping devices. These results were normalized to the treatment absorbed dose at the center depth of the SOBP. The following points were found from the measured results.

1) The measured ambient dose equivalents for the maximum incident proton energy ranged from 1.15 to 2.99 mSv/Gy at 50 cm from the isocenter, and from 0.36 to 0.96 mSv/Gy at 150 cm, with a factor of 2.6-fold difference. The measured ambient dose equivalents for the proton energy around 160 MeV ranged from 0.47 to 0.88 mSv/Gy at 50 cm from the isocenter, and from 0.16 to 0.33 mSv/Gy at 150 cm, with an approximate a factor of 2-fold difference. These results indicate that there can be less than a factor of 3-fold difference in the neutron exposure at beam lines in proton radiotherapy, depending on the operational beam settings used at the facility, and the materials and the locations of the beam line devices. From the comparison of the gantry systems in use at SCC and PMRC, the secondary neutron dose in the proton radiotherapy did not depend on the method for making a laterally-uniform irradiation field. The neutron ambient dose equivalents at



a) Maximum beam energy at each beam line b) Proton energy around 160 MeV

Fig. 2 Measured ambient dose equivalents in the proton and carbon ion radiotherapies[16].

NCCHE were higher than at the other proton radiotherapy facilities. However, the difference became smaller as the distance from the isocenter increased. This result was expected to be derived from the large irradiated field compared to that of other facilities.

2) The neutron exposure in carbon radiotherapy was equal or less than that in proton radiotherapy. As shown Fig. 2, the neutron ambient dose equivalents for 400 MeV/n carbon ions were similar to those for 160 MeV protons. In addition, considering the relative biological effectiveness of the carbon beams for the target volume, the neutron exposure in carbon ion radiotherapy was lower by 1/2.36, which is the RBE value used at NIRS for the carbon beam, because the results were normalized to the treatment absorbed dose at the center depth of the SOBP.

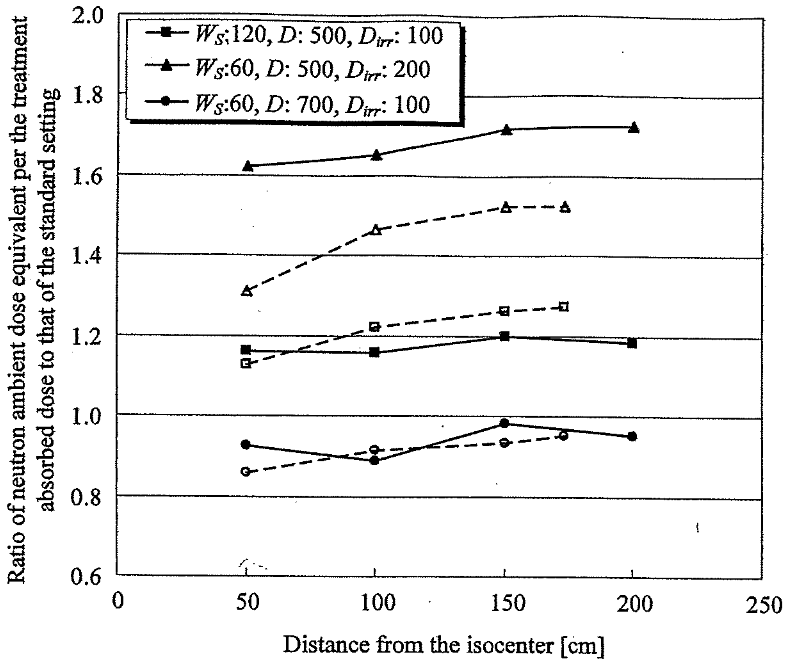
3) The secondary neutron dose in charged particle radiotherapy depended on the SOBP width, and the distance between the irradiation nozzle and the isocenter, but, it almost independent of the incident particle energy as shown in Fig. 3.

The legends show the beam species, the energy and facility. "p" and "C" indicate the beam species of protons and carbon ions, respectively. The values following p and C indicate the beam energy in MeV/n. The values from reference[10] were multiplied by 1/5 for comparison. The value of D_{irr} indicates the diameter of the laterally uniform irradiation field in mm.

The values of W_s, D and D_{irr} in the legend indicate the SOBP width, the distance between the final collimator and the isocenter and the diameter of the laterally uniform irradiation field in mm, respectively.

5. Conclusion

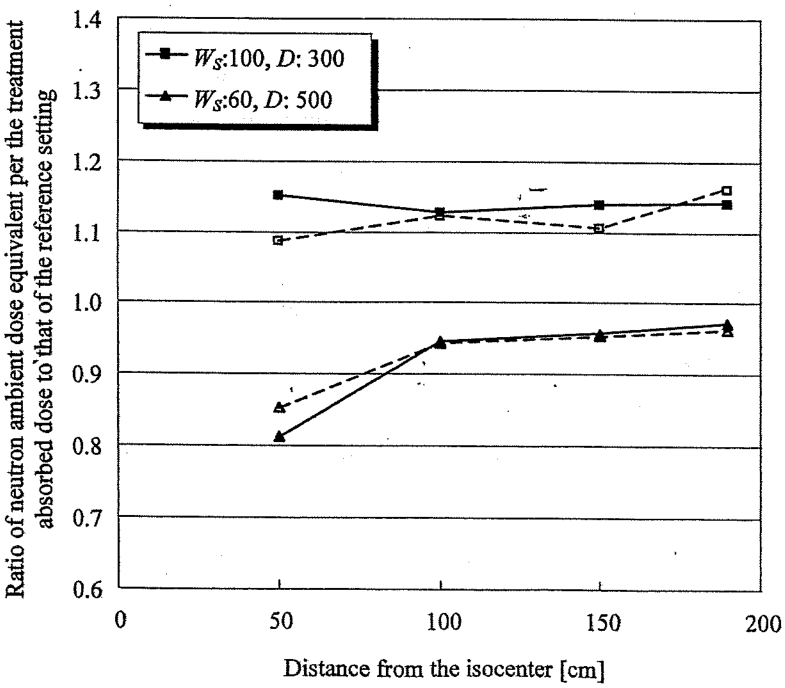
The current status in several foreign countries was investigated regarding radiation safety aspects of charged particle radiotherapy. These therapy facilities were controlled by the same laws as for ordinary accelerator facilities. Experiments at some Japanese facilities were performed. Their results showed that the exposures of medical staff members and a patient's family members, and the radioactivity



a) Carbon ion beam at NIRS.

(The standard settings are Ws=60, D=500 and D_{irr}=100.)

(Black symbols and solid line: 400 MeV/n, open symbols and broken line: 290 MeV/n)



b) Proton beam at NCCHE.

(The standard settings are Ws=60, D=300.)

(Black symbols and solid line: 235 MeV, open symbols and broken line: 150 MeV)

Fig. 3. Neutron ambient dose equivalents with different parameter settings of the beam-shaping devices.[16)]

concentrations in the environments were far below the Japanese legal limits which are the same as the recommendations of the ICRP. We concluded that the present legal controls for ordinary accelerator facilities are sufficient for charged particle radiotherapy facilities.

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Appendix I.

Measurements of radioactivity induced in charged particle radiotherapy

A measurement working group was established within the study to assess radiation exposure from radioactive devices and patients which is induced in the charged particle radiotherapy. The group formulated a protocol for the measurements. The protocol was followed to make measurements at four radiotherapy facilities in Japan. The protocol and the measured results are shown here.

A. *Facilities*

Measurements were performed at the following four facilities.

* Proton Medical Research Center, Tsukuba University (PMRC)
* Shizuoka Cancer Center (SCC)
* Heavy Ion Medical Accelerator in Chiba, National Institute of Radiological Sciences (NIRS)
* Hyogo Ion Beam Medical Center (HIBMC)

B. *Measurement protocol*

The measurement protocol formulated by the working group is shown below. The protocol was followed as much as possible, but was suitably modified when facility-specific problems arose.

1. Projectile beam

1.1. Energy

- Protons: Energy corresponding to the range in water of about 250 mm
- Carbon ions: Energy corresponding to the range in water of about 150 mm and 250 mm

1.2. SOBP width

- 60 mm

1.3. Irradiation beam size

- 150 mm in diameter

1.4. Dose irradiated in one measurement (defined as absorbed dose at the center of the SOBP)

- 5 Gy

1.5. Dose rate

- Based on a dose rate at the treatment

2. Detector

- Ion chamber survey meter was used for measurements with and without a build-cap.
- The survey meters for which the calibration record was unclear were calibrated in the ^{60}Co calibration field at NIRS.
- The model number and the serial number were recorded.

3. Measurement 1: Radioactivity in the patient collimator

3.1. Target material

- The patient collimator was made of the material generally used at the facility.

3.2. Target size

- Thickness: 300 mm in water equivalent thickness
- Aperture size: 50 mm×50 mm

3.3. Measurement procedure

(1) The dose rates on the collimator and at 300 mm downstream from the collimator were measured immediately after the irradiation for the first set of measurements.

(2) The collimator was removed and taken to a place where the background dose is low, e.g. the treatment room.

(3) The dose rates on the upstream surface of the collimator (the surface of the survey meter is placed close to the collimator) and at 300 mm from the collimator (this distance was defined as that between the effective center of the survey meter and the collimator surface) were measured.

4. Measurement 2: Radioactivity in the bolus

4.1. Target material

- The bolus was made of the material generally used at the facility.

4.2. Target size

- Thickness: 100 mm in water equivalent thickness
- Material configuration: unworked block

4.3. Measurement procedure

(1) The dose rates on the downstream surface of the bolus and at 300 mm downstream from the bolus were measured immediately after the irradiation for the first set of measurements.

(2) The bolus was removed and taken to a place where the background dose is low, e.g. the treatment room.

(3) The dose rates on the upstream surface of the bolus (the surface of the survey meter was placed close to the bolus) and at 300 mm from the bolus (this distance was defined as that between the effective center of the survey meter and the bolus surface) were measured.

5. Measurement 3: Radioactivity in the irradiation device (multi-leaf collimator)

5.1. Target material

- Multi-leaf collimator (MLC)

5.2. Target size

- Aperture size: 50 mm×50 mm

5.3. Measurement procedure

- The dose rates on the downstream surface of the collimator and at the 300 mm downstream of the collimator were measured immediately after the irradiation.

5.4. Measurements for x-rays with the medical electron accelerator

- Measurements for the beam energies of 6 and 10 MV were done on the same way as for the charged particle radiotherapy.
- It was impossible to measure the radioactivity for the 6 MV beam due to the very low dose rate which was comparable to the background level.

6. Measurement 4: Radioactivity in the patient

6.1. Target material

- The same Tough Water Phantom (TWP) was used for all measurements.

6.2. Target size

- Thickness: 300 mm
- The center of the phantom was set at the isocenter.

6.3. Settings for the irradiation field

- The multi-leaf collimator and block collimator were completely open.
- A patient collimator with a square aperture of 100 mm×100 mm was used.
- The distance between the phantom surface and the patient collimator was 500 mm.

6.4. Measurement procedure

(1) The dose rates on the downstream surface of the phantom and at 300 mm downstream from the phantom were measured immediately after the irradiation for a first set of measurements.

(2) The phantom is removed and taken to a place where the background dose is low, e.g. the treatment room.

(3) The dose rates on the upstream surface of the phantom (the surface of the survey meter was placed close to the phantom) and at 300 mm from the phantom (this distance was defined as that between the effective center of the survey meter and the phantom surface) were measured.

6.5 Measurements for x-rays with the medical electron accelerator

- Measurements for x-rays were done by the same procedure using the 10 MV beam and 10×10 cm^2 irradiation field.

7. Other remarks

7.1. Measured quantities

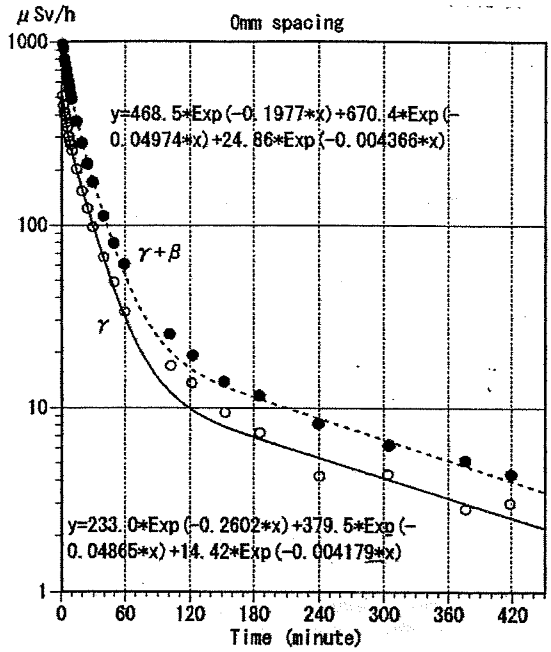
- Dose equivalent ratio of beta-rays and gamma-rays were measured with an ion chamber survey meter (μSv/h).
- Time dependence of the dose rate after the irradiation was measured every 30 s.

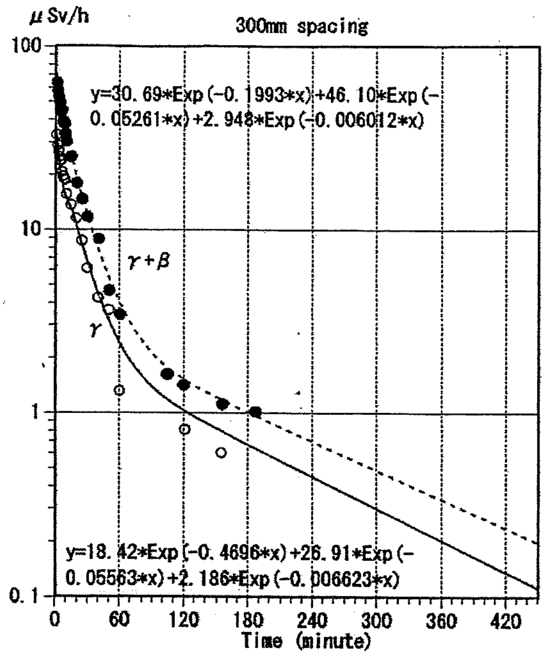
C. Measured results

The measured results obtained according to the above protocol are shown below.

1. PRMC (Proton beam of 200 MeV)

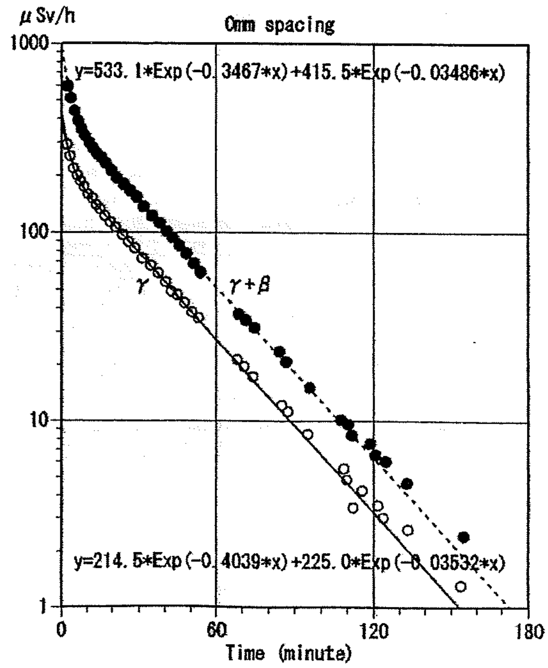
1.1 Measurement 1: Radioactivity in the patient collimator

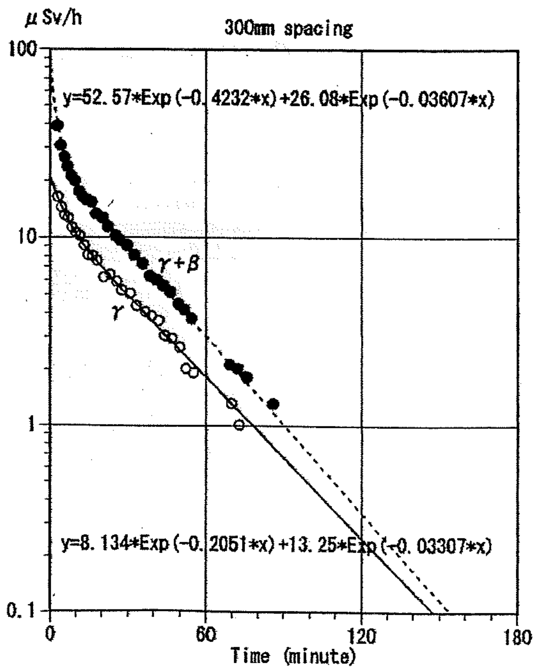




5Gy, proton, 50x50_collimator
pre-collimator: open

1.2 Measurement 2: Radioactivity in the bolus





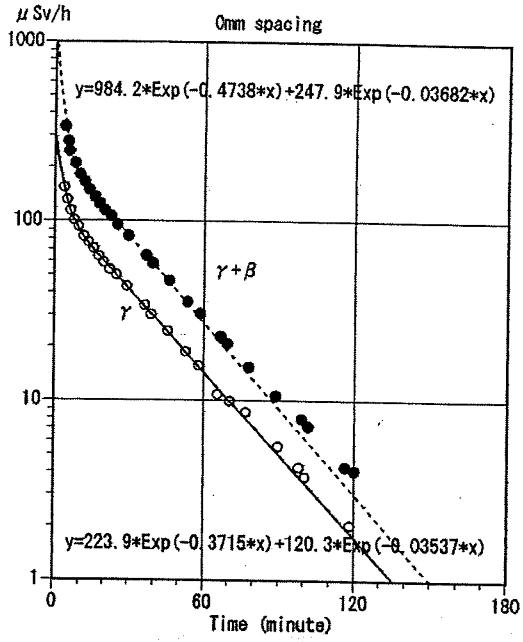
Measurement immediately after the irradiation
downstream surface 0mm, γ 50sec, 542μSv/h
0mm, γ+β 60sec, 950μSv/h

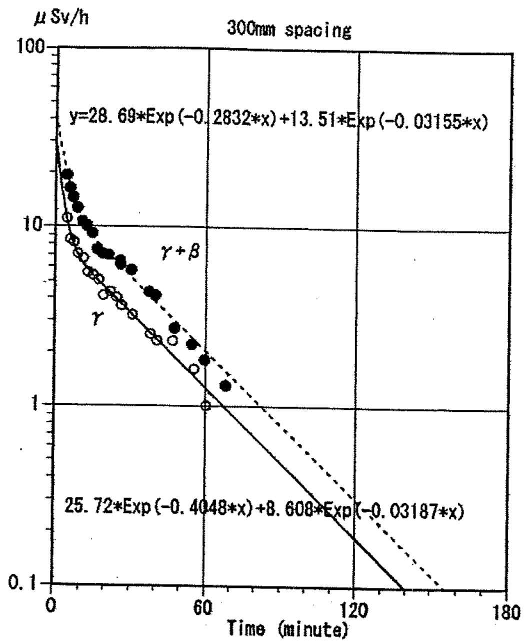
5Gy, proton200MeV, sobp60, 100mm thickness
pre-collimator: open
榮.

1.3 Measurement 3: Radioactivity in the irradiation devices (MLC)

- This measurement was not performed.

1.4 Measurement 4: Radioactivity in the patient (TPW)





Measurement immediately after the irradiation

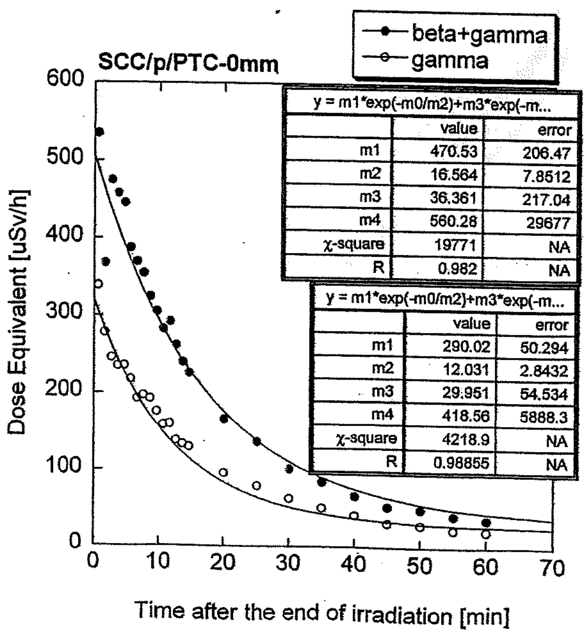
downstream surface	0mm, γ	120sec, 37μSv/h
	0mm, γ+β	130sec, 37μSv/h
	300mm, γ	150sec, 6.6μSv/h
	300mm, γ+β	160sec, 7.2μSv/h

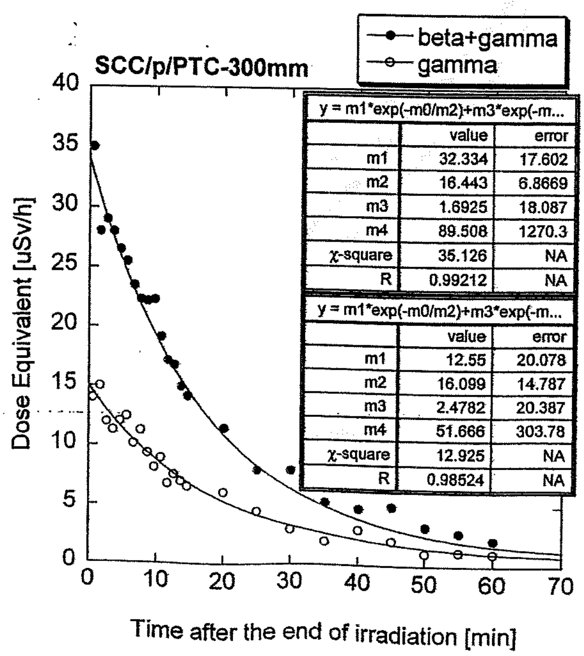
5Gy, proton200MeV, sobp60, Tough Water 300x210x300
beam size 100x100mm, pre-collimator: open

2. SCC (Proton beam of 220 MeV)

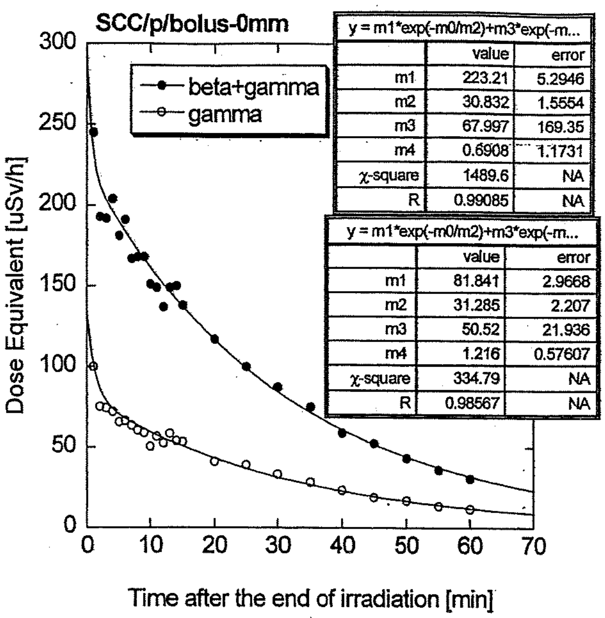
※There is a possibility that these measured results of the patient collimator, the bolus and the Tough Water Phantom were underestimated due to the self-shielding effect, because the measurements were made on the downstream surface.

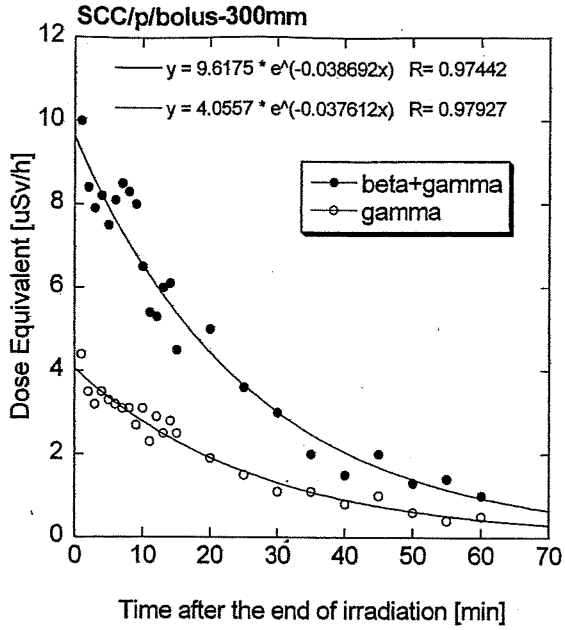
2.1 Measurement 1: Radioactivity in the patient collimator





2.2 Measurement 2: Radioactivity in the bolus





2.3 Measurement 3: Radioactivity in the irradiation device (MLC)