SUBSIDIARY NEUTRON DOSE TO PATIENTS WITH PROTON THERAPY

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INTRODUCTION

In the treatment planning of proton beam irradiation, owing to its excellency in dose distribution, radiologists can administrate doses larger than those in the conventional therapy with high energy X-rays. The remarkable performance of the proton therapy with deep-seated tumors is now widely recognized[1]. In the irradiation port of proton beam, collimators and other devices inserted upstream of the beam to the patient interrupt a considerable part of the protons bearing kinetic energy up to 200 MeV. As is well known, high energy protons can generate high energy neutrons when they interact with matter[2]. These strongly penetrating neutrons cause subsidiary exposure to the patient treated with proton beam. One of the authors (Takada) had estimated that transporting efficiency of the irradiation facility employing so-called (single) scattering method is ten percent or so at best[2]. Hence, for the purpose of providing information in making a clinical decision to select the treatment modality and for radiation protection, it is of interest to evaluate these neutron doses and know their importance. Investigations were made at the Proton Medical Research Center (PMRC), the University of Tsukuba.

A CRUDE ESTIMATION OF SUBSIDIARY NEUTRON DOSE

Firstly, we show a crude estimation of the patient neutron dose based on a simplified model. The configuration of collimators in the vertical irradiation port of PMRC is depicted in Fig.1. Assuming that the protons propagate as a corn shaped beam from the scatterer with the two-dimensional Gaussian distribution in the plane perpendicular to the beam axis, it is estimated that ten per cent of protons incident on the beam port are interrupted by the Upper Collimator (UC), fifty per cent by the Lower Collimator (LC), and at least thirty per cent by the Block Collimator (BC). According to the typical settings of irradiation control devices for liver tumor (a common cancer in Japan) treatment, kinetic energy of protons are approximately 180 MeV at UC and 135 MeV (in average) at LC and BC. The data of IAEA[3] (Fig.2) shows that protons of 180 MeV and of 135 MeV stopped in a copper target generate about 0.6 and 0.3 neutrons per proton, respectively.

The fluence of proton beam at this treatment is evaluated as follows. The spectrum of proton beam at the frontal edge of the spread-out Bragg peak (SOBP), $\Phi(E_i)/\Phi$, can be derived form the design shape of the ridge filter. With thus-calculated spectrum, the absorbed dose to water in the region of SOBP by unit fluence of protons, D/Φ, is estimated as a weighted average of mass collision stopping power of water (Fig.3). The value of D/Φ being evaluated as 5.9 $MeV/(g/cm^2)$, the proton fluence corresponding to the absorbed dose of 1 Gy at the target volume in this typical situation is estimated as 1.1×10^9 cm^{-2}.

The calculated value of conversion coefficient from neutron fluence to dose equivalent at 10 mm depth in the tissue equivalent slab[4] varies only 10 % in the energy region between 2 MeV and 100 MeV. So, the value at 10 MeV, 7.2×10^{-10} $Sv\cdot cm^2$ (factor 2 is multiplied following the 1985 Statement of ICRP), is used in this estimation.

The subsidiary neutron dose of 0.01 Sv per 1 Gy of proton dose at the tumor region is obtained in this estimation. The results are summarized in Table 1.

MONITORING OF SUBSIDIARY NEUTRON DOSE BY SODIUM ACTIVATION

The time structure of the proton beam at PMRC being strongly bunched (FWHM = 50 ns), conventional methods of neutron dosimetry are not applicable. Therefore, measurement of activated urinary sodium of the patient is utilized to estimate thermal neutron fluence through the body. There are many materials, *e.g.*, ^{109}Ag and ^{195}Au, being used for activation analysis, but of these materials only sodium is suitable for our purpose. Because, the quantity that is important in clinical decision making is not a neutron fluence at some specified point on the patient, but the averaged fluence throughout the body. Sodium, the ninth most abundant element in the human body (0.08 %), and having large capture cross section (474 mb) is the most adequate material for this purpose. Urinary sodium is always in equilibrium with blood serum sodium. The ratio of sodium concentration in urine and in blood serum is almost constant with a value of 0.5[5]. Thus, we can obtain average thermal neutron fluence by measuring the activation of urinary sodium.

To confirm the feasibility of this idea, sodium activation measurement was conducted with a patient who was administrated 3 Gy of proton dose to an abdominal tumor. The urine was sampled about 20 minutes after the irradiation. The radioactivity of 9.5×10^{-1} (±13 %) Bq of ^{24}Na at the time of irradiation was measured with the urine sample of 50 cm^3. Using the normal concentration of urinary sodium (7×10^{-5} mol/cm^3), average thermal neutron fluence is estimated as 3.7×10^{7} cm^{-2}. Thus, the thermal neutron dose to this patient is evaluated as 0.6 mSv using the conversion coefficient for thermal neutrons given by ICRP[4].

Neutrons are thermalized in the matter surrounding the patient as well as in the body of the patient itself. A series of phantom experiments were conducted to verify which is dominant. The amount of activation of NaCl solution set inside the phantom (polyethylene, cubic) decreased when bottom part of the phantom was removed. The result shows that the thermalization in the body of the patient is dominant.

In order to estimate from the thermal neutron fluence, knowledge of the neutron spectrum is needed. The spectrum of neutrons to which the patient is exposed, however, is influenced by the configuration of irradiation control devices such as collimators, filters and degraders. As a result, the spectra are each different. However, detailed structure of each spectrum is not so important for our purpose, because it is sufficient to know the ratio of subsidiary neutron dose to the administrated proton dose, and moreover the value of dose equivalent is not so sensitively affected by the detailed structure of neutron spectrum. So, a computer simulation was conducted to obtain a neutron spectrum in the phantom with a "typical" configuration of irradiation control devices. The HERMES[6] code was used to simulate generation and propagation of high energy neutrons. To simulate transportation of fast and slow neutrons, the DOT[7] and ANISN[8] codes were employed.

A sample of geometries and spectra in the numerical analysis are shown in Figs. 4 and 5. In this case, the neutron spectrum is considered to be the "hardest", since neutrons are generated just upstream the phantom. The dose due to whole neutrons is estimated about 25 times of thermal neutron dose from this investigation.

Consequently, the subsidiary neutron dose per unit dose of administrated protons is estimated about 5 mSv/Gy.

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FIG.1 COLLIMATORS OF VIRTICAL LINE

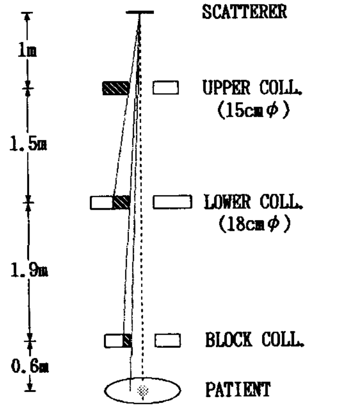


FIG. 2 NEUTRON YIELD PER PROTON (n/p)

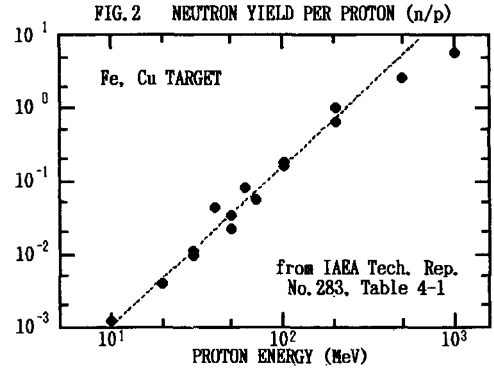
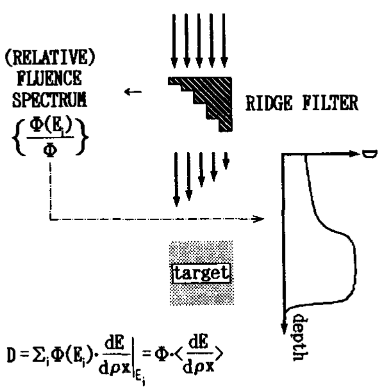


Fig. 3 EVALUATION OF PROTON FLUENCE



$$D = \Sigma_i \Phi(E_i) \cdot \frac{dE}{d\rho x}\Big|_{E_i} = \Phi \cdot \langle \frac{dE}{d\rho x} \rangle$$

TABLE 1 ESTIMATION OF SUBSIDIARY NEUTRON DOSE*

	UPPER COLLIMATOR	LOWER COLLIMATOR	BLOCK COLLIMATOR
PROTONS INTERRUPTED	2.2×10^{11} [p/Gy]	1.1×10^{12} [p/Gy]	6.6×10^{11} [p/Gy]
PROTON ENERGY	180 MeV	135 MeV	135 MeV
NEUTRON GENERATION	0.6 [n/p]	0.3 [n/p]	0.3 [n/p]
NEUTRON YIELD	1.3×10^{11} [n/Gy]	1.2×10^{11} [n/Gy]	1.9×10^{11} [n/Gy]
NEUTRON DOSE EQUIVALENT	1.9×10^{-4} [Sv/Gy]	1.2×10^{-3} [Sv/Gy]	1.2×10^{-2} [Sv/Gy]

* NEUTRON DOSE EQUIVALENT PER UNIT TARGET PROTON DOSE

FIG. 4 GEOMETRYOFSIMULATION

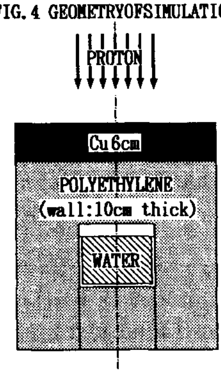


FIG. 5 NEUTRON FLUENCE IN PHANTOM