SECONDARY NEUTRON PRODUCTION FROM PATIENTS DURING HADRON THERAPY AND THEIR RADIATION RISKS:THE OTHER SIDE OF HADRON THERAPY

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Abstract

By making use of the experimental neutron production data from different body elements we have estimated the fluence and energy distributions of the secondary neutrons from patients' tissues under irradiation with protons and C-ions. Our results indicate that at least 4.2 neutrons, with energies greater than 5 MeV, are produced for every C-ion of 400MeV/u energy incident on the patients' tissues. This number reduces to 3, 1.4 and 0.3 respectively at C-energies of 300, 200 and 100 MeV/u. For protons these numbers are estimated to be 0.05, 0.2 and 0.4 per proton of energies 100, 200 and 300 MeV respectively. There would, no doubt, be even more neutrons with energies lesser than 5 MeV but we could not estmate these due to the non-availability of the experimental data. The doses to some organs in the immediate vicinity of the hadron beam have been estimated, which are not negligible. A " Compromise-Optimum-Energy" concept is suggested. However, extreme caution is highly recommended before treating patients with hadrons, especially children and younger persons who still have many years to live.

INTRODUCTION

Radiotherapy treatment of different types of cancers with protons is being conducted in many institutions around the world, and a few institutions are also treating patients with carbon ions. A few more organizations are also planning to have C-ions therapy available, even when these machines are a lot more expensive than proton machines. However, in spite of all this activity and interest in hadron therapy, it is surprising that the matter of secondary neutron production from patients, and its potential implications, has not been given due attention. We were the first group in the world who accurately and unambiguously calculated and experimentally determined the fluence and energy distributions of secondary neutrons produced from patients undergoing therapy with Bremsstrahlung [1]. A lot more neutrons would be produced by patients" tissues under irradiation with hadrons due to their much larger neutron producing reaction cross sections. We were again the first group to point this fact and cautioned about the use of hadrons for treatment, especially in the case of children and younger persons [2].

METHOD AND MATERIALS

There appears to be no accurate and "meaningful" measurements or calculations in the literature, on neutron production from tissue under bombardment with hadrons. Some measurements do exist but these give the neutron output NOT AT THE SOURCE but some distance away from where the neutrons are being produced and no account is made for any scattering or absorption of the neutrons in the body itself or in the atmosphere. However, experimental data is available where neutron yields from thick- targets of C and other heavier elements have been studied for carbon ion incident energies of up to 400 MeV/u [3], which covers the energy range being actually used in therapy . It is shown that the secondary neutrons produced have energies ranging from 5 MeV to twice the incident carbon- ion energy per nucleon with a broad peak, at about 60-70 % of the incident carbon-ion energy, in the forward direction.

Furthermore, it is also pointed out by the authors, Kurosawa et al [3], that the dependence of the yield of neutrons with energies greater than 5 MeV (apparently the minimum neutron energy which they could measure), integrated for a hemisphere from 0 to 90°, on the target mass is very small compared with the difference of neutron numbers of the targets. For example the differences in the total yields of neutrons with energies greater than 5 MeV, from thick targets of carbon and aluminium, bombarded with carbon ions of 100, 180 and 400 MeV / u, are only 11.6, 13.0 and 13.6 % respectively, while the differences in the neutron yields from thick carbon and lead targets, are 10.8, 22.4 and 4.4 % respectively at incident carbon ion energies of 100, 180 and 400 MeV / u.. This means that the intensity of the secondary neutrons produced from thick targets of C, N and O would be similar, and at the most no more than around 10-15 % different from each other, under bombardment with C-ions in the energy range being presently considered.

Therefore, based on these observations, one may be justified to use the secondary neutron production yields from a thick target of carbon in order to approximately estimate the numbers of such neutrons produced within patients (tissue), undergoing therapy with carbon ions, as the major constituents of tissue are H, C, N and O with its composition represented by C_5 H_{40} O_{18} N. With similar arguments the fluence and enrgies of neutrons from tissue under bombardment with protons were estimated by making use of the published data.

RESULTS AND DISCUSSION

Our results clearly show that 4.2, 3, 1.4 and 0.3 neutron, with energies greater than 5 MeV, are produced for every C-ions with energy of 400, 300, 200 and 100 MeV /u respectively. Besides these secondary neutrons, there would also be a considerable number of slower neutrons of energies lesser than 5 MeV for which there is no experimental data and therefore could not be included in the present estimation.

Typically, the medium dose per treatment of skull base tumours is around 20 Gy (physical) in the Darmstadt-Heidelberg programme [4].The numbers of C-ions required to impart a dose of 1Gy in tissue in the Bragg Peak are 6.9 x 10^{6}/ cm^{2} , 8.8 x 10^{6} / cm^{2} and 18.7 x 10^{6}/ cm^{2} at carbon ions energies of 100 , 200 and 400 MeV / u. respectively [4]. This means that the total numbers of secondary neutrons, with energies > 5 MeV produced from tissue at incident carbon ions energies of 100, 200 and 400 MeV /u would be 4.1 x 10^{7} / cm^{2}, 2.5 x 10^{8} / cm^{2} and 1.6 x 10^{9} / cm^{2} respectively.

These very large number of neutrons could potentially cause new secondary cancers and could also have other side effects, especially when the high radiobiological effectiveness (RBE) of neutrons is taken into consideration [5].

Kurosawa et al (3) also measured the energy distributions of neutrons produced from thick-carbon-target under bombardment with C- ions of 100, 180 and 400 MeV / u. By making use of the arguments already given one may also be justified to regard these energy spectra as similar to those which would be coming from a tissue target under bombardment with carbon ions. Therefore, from these energy distributions we have been able to estimate the mean-energy of the neutron spectrum to be 29, 50 and 125 MeV respectively at C-ions energies of 100, 200 and 400 MeV /u respectively. We used these values for estimating the “effective whole body dose” as well as doses to a number of organs. The energy spectra are “smooth and slowly varying” and one is, therefore, justified to take the mean-energy of the secondary neutrons spectra in order to estimate the dose contributions, rather than calculating doses at all the energies.

In order to estimate the radiation doses to the whole body and to different organs we made use of the tabulations of Bozkurt et al [6] which give fluence- to-dose conversion coefficients, at different neutron energies, based on their VIP-Man (Visible Photographic Man).

Our results show that for a physical dose of 20 Gy in the Bragg peak, the effective whole body doses due to these secondary neutrons are 18, 114 and 955 mSv cm ^2 respectively at C-ion energies of 100, 200 and 400 MeV/u [Table 1] Furthermore, we have also estimated the doses to 24 body organs due to these secondary neutrons for different incident geometries, again by using the tabulations of Bozkurt et al [5].The results are shown in table 2 for three different incident geometries ; anterior-posterior (AP), posterior-anterior (PA), and isotropic (ISO).**However, these figures are valid only if all the neutrons produced are incident on the organ in question, which can only happen if the organ happens to in the immediate vicinity of the incoming beam. .If it is not the case one has to estimate the reduction in the neutron fluence reaching the said target and then estimate the respective doses.**

It can be seen from our results that the effective whole body doses of around 18, 114 and and 955 mSv cm^{2}, are imparted by these secondary neutrons coming from patients’ tissue at incident C-ion energies of 100, 200 and 400 MeV /u respectively. The corresponding doses to different organs range from 15-30 and 130-230 mGy cm^{2} at incident Carbon-ion energies of 200 and 400 MeV /u respectively. These doses are definitely not insignificant, especially when the radiation weighting factor for neutrons is taken into consideration for estimating the absorbed doses to different organs.

According to Brenner et al [6] “ good evidence exists of increased cancer risks in humans for acute exposure of 10-50 mSv “. Therefore, the secondary neutrons produced by patients’ tissues at incident carbon-ion energies of 200 MeV / u and above have the real potential of causing new cancers.

In order to overcome this problem we are suggesting the concept of ***“A Compromise Optimum Energy”*** which is the minimum adequate incident energy to treat the tumour, thus having the “advantage of C- beam” but still producing the least amount of secondary neutrons from the patients’ tissues, In such cases we might have to irradiate the patients from different directions and angles, which is not always convenient. However, we still think it is a better alternative than to produce a lot more secondary neutrons, by using higher C-energies which can only be harmful to the patients.

CONCLUSIONS

Our estimations clearly show that a very large number of secondary neutrons are produced by patients ndergoing therapy with C-ion beams, especially at energies of 200 MeV / u and higher. The estimated whole body effective dose and the doses to different organs are not insignificant and have the real potential to cause new cancers in the patients. In order to partially overcome this problem we are suggesting the concept of “Compromise Optimum Energy” However, it is still strongly recommended that, very careful considerations must be given before deciding to treat patients with hadrons, especially children and younger persons who still have many years to live. The case of neutron production from patients under irradiation with with protons would be published elsewhere. However, it can be mentioned here that, although the secondary neutrons produced per protons at different energies is much smaller than those produced by C-ions, the total number of neutrons produced per treatment are similar. This is due to the fasct that many more protons are needed to impart the same dose as C-ions of similar energies, because we need many more protons to give the same dose.

Furthermore, on the basis of our results, we would like to point out that the large "RBE (Radio-biological-effectiveness) observed with C-ions could most likely be due to the presence of so many secondary neutrons produced from tissue. It is universely accepted that the neutrons have rather high RBE, therefore enhansing the RBE of the carbon-beams giving rise to these secondary neutrons.

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Table 2

Carbon ion energy	**200 MeV / u**			**400 MeV / u**		
Incident geometry	**Radiation doses mGy**					
ORGAN	**AP**	**PA**	**ISO**	**AP**	**PA**	**ISO**
Adrenals	23	23	21	214	200	208
Bladder walls	26	24	20	205	205	198
Bone	15	15	13	136	147	137
Brain	23	24	23	187	181	184
Breast	20	24	22	105	208	163
Esophagus wall	26	24	22	205	203	190
Eye lenses	24	17	21	128	168	152
Heart wall	26	25	21	201	211	200
Kidney	24	26	21	211	222	202
Liver	24	24	21	205	211	198
Lower large intestine	27	24	21	206	216	195
Lungs	25	25	21	197	200	190
Muscle	24	24	21	186	184	182
Pancreas	24	23	21	203	211	197
Prostate	25	26	21	229	216	213
Red bone marrow	22	23	19	200	200	189
Skin	19	19	18	137	140	140
Small intestine	26	23	21	203	213	194
Spleen	22	25	22	210	198	192
Stomach wall	24	23	21	203	214	192
Testes	25	22	21	132	220	179
Thymus	24	21	19	173	190	186
Thyroid	30	23	21	162	224	184
Upper large intestine	26	23	21	189	213	195

Table 1

Incident energy of C-ions (MeV/n)	Number of C-ions to impart one Gy dose in the Bragg-Peak / cm^{2}	Average energy of the secondary neutrons (MeV)	Number of neutrons, with energies greater than 5 MeV per C-ion	Total number of neutrons, with energies greater than 5 MeV produced for a physical C-ion dose of 20 Gy in the Bragg-Peak	Estimated Effective dose due to secondary neutrons [ref. 4] (mSv)
100	6.9 x 10^{6}	29	0.3	4.1 x 10^{7}	18
200	8.8 x 10^{6}	50	1.4	2.5 x 10^{8}	114
300	12.2 x 10^{6}		3	7.3 x 10^{8}	
400	18.7 x 10^{6}	125	4.2	1.6 x 10^{9}	955