Case Report

Bremsstrahlung dose of therapeutic beta nuclides in bone and muscle

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ABSTRACT In the nuclear medicine, beta nuclides are released during the treatment. This beta interacts with bone and muscle and produces external Bremsstrahlung (EB) radiation. Present work formulated a new method to evaluate the EB spectrum and hence the Bremsstrahlung dose of therapeutic beta nuclides (Lu-177, Sr-90, Sm-153, I-153, Cs-137, Au-201, Dy-165, Mo-99, Sr-89, Fe-59, P-32, Ho-166, Sr-92, Re-188, Y-90, Pr-147, Co-60, K-42) in bone and muscle. The Bremsstrahlung yields of these beta nuclides are also estimated. Bremsstrahlung production is higher in bone than that of muscle. Presented data provides a quick and convenient reference for radiation protection and it can be quickly employed to give a first pass dose estimate prior to a more detailed experimental study.

Keywords: Beta dosimetry, beta medicine, bremsstrahlung dose, bremsstrahlung spectrum

INTRODUCTION

In the therapeutic nuclear medicine, application of incorporated beta emitting radionuclides finds extremely high potential in the treatment of both malignant and non-malignant conditions. The beta emitting nuclides are also used for therapy of non-malignant conditions like radiosynovectomy. This includes the treatment of painful conditions associated with disease of joints such as rheumatoid arthritis or villonodular synovitis.[1] After careful evaluation and diagnosis, a small amount of radioisotope is injected into the joint. These radioisotopes emit beta rays, which penetrate only from fraction of a millimeter to a few millimeters and destroy the inflammatory tissue and thus reduce swelling and pain. Beta emitting nuclides such as Y-90, P-32, Dy-265, etc., offers clinically proven and cost-effective alternative to surgical synovictomy.[2] Uchiyama *et al.*[3] reported that Sr-89 chloride is being widely used as a palliative treatment for patients with bone pain caused by bone metastases. The radio nuclides such as Sr-89 and P-32 have also been successfully and effectively utilized to provide palliative therapy to patients with multifocal skeletal metastatic lesions in cases of breast and prostatic cancers. Furthermore, Y-90 appears to be a potential beta emitting radionuclide, which has been shown to offer attractive considerations for being used in radioimmunotherapy.[4] In radioimmunotherapy, beta nuclide delivers lethal dose of radiation directly to cancerous tumor cells there by reducing the radiation exposure to surrounding tissues. Beta emitting radionuclide like P-32 also finds application in infusional brachytherapy.[5] The incorporated therapeutic beta emitting nuclides produces Bremsstrahlung radiation and could have different energies and intensities. The Bremsstrahlung component of beta emitters has been traditionally ignored in internal dosimetry calculations. This may be due to a lack of available methods for including this component in the calculations or to the belief that the contribution of this component is negligible compared to that of other emissions. The resulting hazard of Bremsstrahlung radiation released during beta therapy may therefore be of some concern, at least theoretically and should be systematically evaluated. In the present investigation, it has been estimated that the Bremsstrahlung spectrum and dose of therapeutic nuclides (Lu-177, Sr-90, Sm-153, I-153, Cs-137, Au-201, Dy-165, Mo-99, Sr-89, Fe-59, P-32, Ho-166, Sr-92, Re-188, Y-90, Pr-147, Co-60, K-42) in bone and muscle.

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PRESENT WORK

Estimation of external Bremsstrahlung (EB) cross-section

Markowicz and VanGriken[6] proposed an equation (1) to take into account the self-absorption of Bremsstrahlung and electron

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back scattering and to obtain the accurate description of the Bremsstrahlung process

$$I = \text{Const}\,\frac{\Delta E}{E_\gamma} Z_{mod}\,(E_0 - E_\gamma)[1 - f] \quad (1)$$

Here,
$$Z_{mod} = \frac{\sum_i^l \frac{W_i Z_i^2}{A_i}}{\sum_i^l \frac{W_i Z_i}{A_i}} \quad (2)$$

A_i, W_i and Z_i are mass number, weight fraction and atomic number of the i^{th} element respectively, f is a function of E_0, E_γ and composition. The modified atomic number Z_{mod} defined for compound is more accurate[7] one than Z_{mean}. The six elements whose atomic numbers adjacent to that of bone (Z_{mod} = 10.2509) chosen are N, O, F, Ne, Na and Mg and their *Z* values are 7, 8, 9, 10, 11 and 12 respectively. Z_{mod} is evaluated using equation (2) and their composition.[8] The EB cross-section is evaluated using Lagrange's interpolation technique, Seltzer-Berger[9] theoretical EB cross-section data given for elements using the following equation

$$\sigma_{Z\text{mod}} = \sum \left(\frac{\prod_{Z_{mod} \neq Z} (Z_{mod} - Z)}{\prod_{z \neq Z} (z - Z)} \right) \sigma_z \quad (3)$$

where, lower case z is the atomic number of the element of known EB cross-section σ_z adjacent to Z_{mod} of the compound whose EB cross-section $\sigma_{Z\text{mod}}$ is desired and upper case Z are atomic numbers of other elements of known EB cross-section adjacent to Z_{mod}. Similarly, we have evaluated cross-section for muscle.

Evaluation of Bremsstrahlung spectrum

The number *n* (T, k) of EB photons of energy k when all of the incident electron energy T completely absorbed in thick target is given by Bethe and Heitler[10] is

$$n\,(\mathrm{T, k}) = \mathrm{N}\int_k^T \left(\frac{\sigma(\mathrm{E, k})}{(-\mathrm{dE/dx})} \right) \mathrm{dE} \quad (4)$$

where, σ (E, k) is EB cross-section at photon energy k and electron energy E, N is the number of atoms per unit volume of target and E is the energy of an electron available for an interaction with nucleus of the thick target after it undergoes a loss of energy per unit length (−dE/dx). For a beta emitter with end point energy T_{max}, spectral distribution of EB photons (S [k]) is given by

$$\mathrm{S(k)} = \frac{\int_T^{T_{max}} n(\mathrm{T, k})\,\mathrm{P(T)\,dT}}{\int_T^{T_{max}} \mathrm{P(T)\,dT}} \quad (5)$$

where P (T) is the beta spectrum. Evaluated results of σ (E, k) of equation (3) and tabulated values of (−dE/dx) of Seltzer-Berger data are used to get S (k) for the target compounds.

Evaluation of Bremsstrahlung yield

The number of EB photons produced by electrons or beta particle while passing through a thick target enough to absorb them can be defined as photon yield (N) of the target. Energy yield (I) is the total Bremsstrahlung energy radiated per incident beta particle. EB photon yield (N) and energy yield (I) are evaluated from S (k) from the following equations

$$N = \int_{k_{min}}^{k_{max}} S(k)\,dk \quad \text{and} \quad I = \int_{k_{min}}^{k_{max}} k S(k)\,dk \quad (6)$$

where k is the photon energy, k_{min} and k_{max} are the minimum and maximum energy of the measured photon spectrum.

Evaluation of Bremsstrahlung dose

We have used the following equation[11] for the calculation of

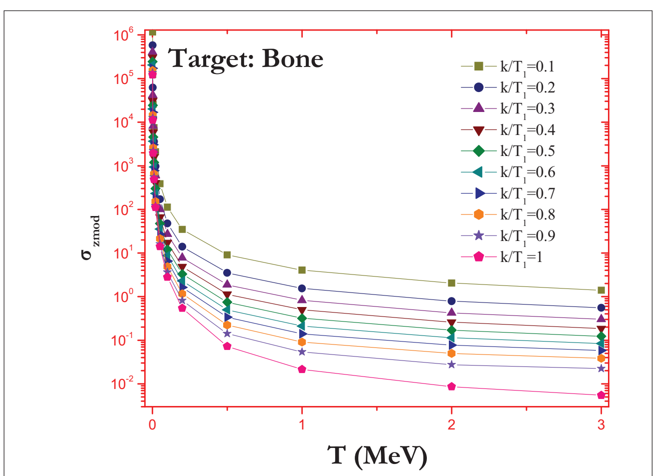

Figure 1: Variation of Bremsstrahlung cross-section with energy for bone (here k and T are outgoing photon and incident electron energies respectively)

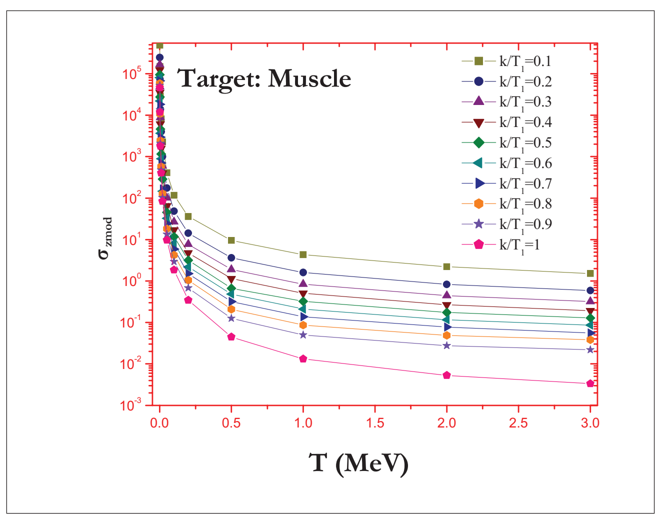

Figure 2: Variation of Bremsstrahlung cross-section with energy for muscle

specific absorbed fraction of energy at distance x from the point source monoenergetic photon emitter

$$\Phi(x) = \frac{\mu_{en} \exp(-\mu x) B_{en}}{4\pi x^2 \varrho} \qquad (7)$$

Here, μ_{en} is linear absorption coefficient of photons of given energy, μ is linear attenuation coefficient of photons of given energy, B_{en} is energy absorption build up factor; ϱ is density of the medium. The energy absorption build up factors has been computed using Geometric progression fitting method.[12] The values of μ_{en} and μ of photons have been taken from Hubbel.[13] The specific absorbed fraction for a given beta source was estimated by integrating over the entire Bremsstrahlung spectrum using the following equation (8).

$$\Phi(x) = \int_0^{T_{max}} \Phi_T(x)\, dT \qquad (8)$$

where T_{max} is the maximum energy of beta. Estimation of the value of Φ allows calculation of the absorbed dose at fixed distances from the point source in the infinite, homogeneous medium

$$D(x) = \tau \sum \Delta_i \Phi_i(x) \qquad (9)$$

where D (x) is the absorbed dose at distance × per unit initial activity (Gy/MBq); τ is the residence time of activity; and Δ is the mean energy emitted per unit cumulated activity and it is numerically equal to (2.13 $n_i E_i$), where n_i is the frequency of occurrence of emissions with energy E_i; the quantities n and E are provided by the calculated Bremsstrahlung spectrum using equation (5).

RESULTS AND DISCUSSION

The estimated σ_{Zmod} (barn/MeV) for bone and muscle are shown in Figures 1 and 2 respectively. In the Figures 1

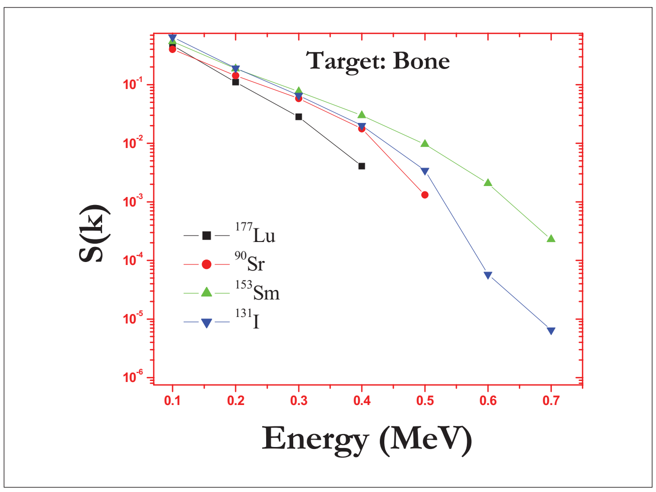

Figure 3: Beta induced Bremsstrahlung spectra, S (k) (in number of particles/ m_0C^2/beta) of bone

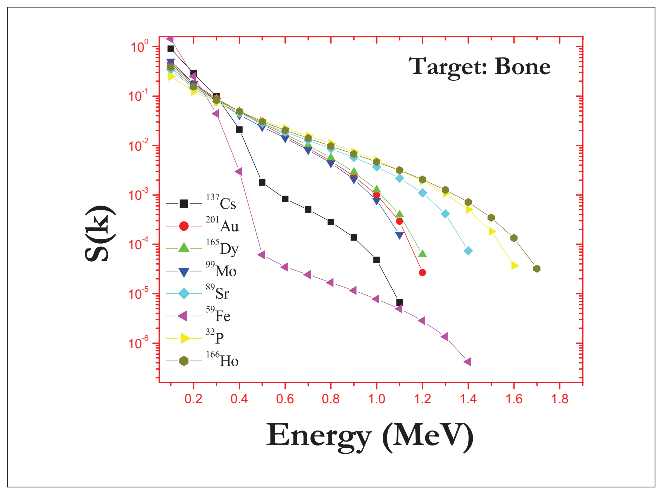

Figure 4: Beta induced Bremsstrahlung spectra, S (k) (in number of particles/ m_0C^2/beta) of bone

Table 1: Properties of therapeutic beta isotopes used in the present study

Nuclides	E_{max} (MeV)	E_{Br} (MeV)	Bone		Muscle	
			N (protons/beta)	I (MeV/beta)	N (protons/beta)	I (MeV/beta)
^{177}Lu	0.498	0.055	6.084E−02	7.878E−03	6.011E−02	7.772E−03
^{90}Sr	0.546	0.060	6.222E−02	9.394E−03	6.139E−02	9.244E−03
^{153}Sm	0.808	0.089	8.505E−02	1.330E−02	8.389E−02	1.308E−02
^{131}I	0.970	0.107	9.299E−02	1.327E−02	9.180E−02	1.307E−02
^{137}Cs	1.175	0.129	1.318E−01	1.884E−02	1.301E−01	1.856E−02
^{201}Au	1.263	0.139	8.379E−02	1.645E−02	8.248E−02	1.611E−02
^{165}Dy	1.286	0.141	7.956E−02	1.622E−02	7.829E−02	1.587E−02
^{99}Mo	1.357	0.149	8.680E−02	1.607E−02	8.550E−02	1.574E−02
^{89}Sr	1.495	0.164	6.905E−02	1.586E−02	6.787E−02	1.547E−02
^{59}Fe	1.565	0.172	1.745E−01	2.094E−02	1.725E−01	2.068E−02
^{32}P	1.710	0.188	5.977E−02	1.605E−02	5.864E−02	1.561E−02
^{166}Ho	1.854	0.204	7.643E−02	1.792E−02	7.512E−02	1.746E−02
^{92}Sr	1.940	0.213	2.102E−01	2.917E−02	2.075E−01	2.875E−02
^{188}Re	2.120	0.233	7.339E−02	1.848E−02	7.206E−02	1.798E−02
^{90}Y	2.280	0.251	6.132E−02	1.669E−02	6.016E−02	1.620E−02
^{147}Pr	2.686	0.295	9.750E−02	2.385E−02	9.578E−02	2.322E−02
^{60}Co	2.823	0.311	1.714E−01	1.902E−02	1.695E−01	1.881E−02
^{42}K	3.525	0.388	5.341E−02	1.684E−02	5.231E−02	1.626E−02

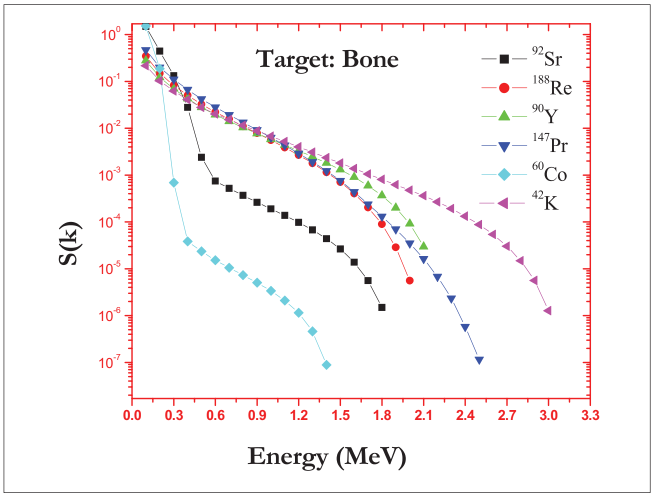

Figure 5: Beta induced Bremsstrahlung spectra, S (k) (in number of particles/m_0C^2/beta) of bone

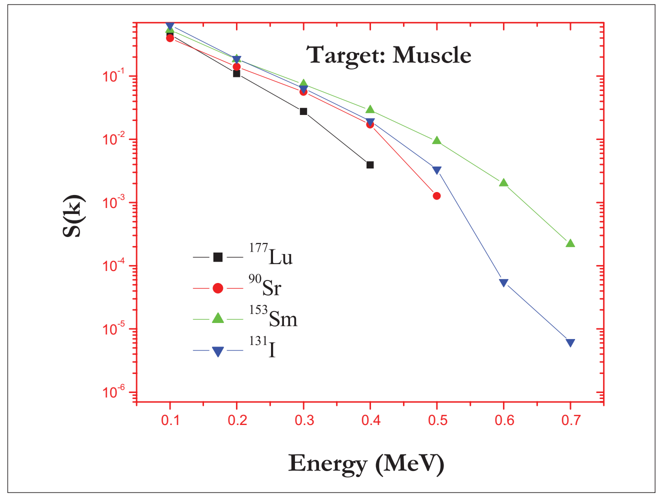

Figure 6: Beta induced Bremsstrahlung spectra, S (k) (in number of particles/m_0C^2/beta) of muscle

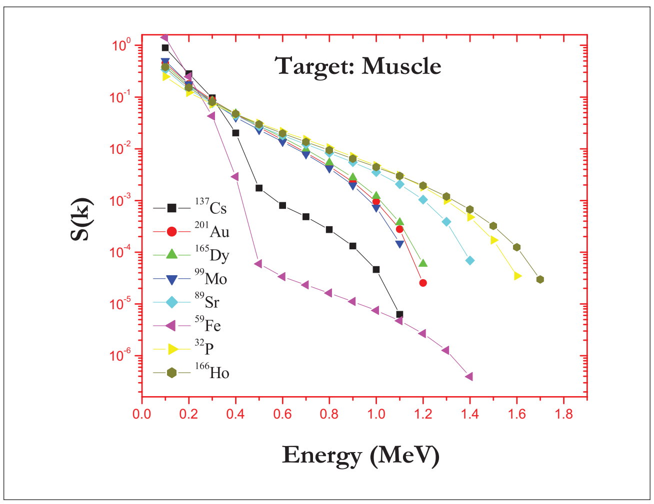

Figure 7: Beta induced Bremsstrahlung spectra, S (k) (in number of particles/m_0C^2/beta) of muscle

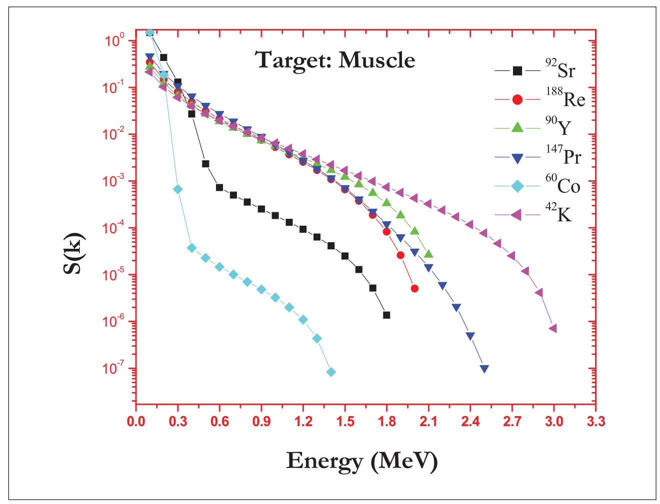

Figure 8: Beta induced Bremsstrahlung spectra, S (k) (in number of particles/m_0C^2/beta) of muscle

Table 2: Evaluated beta induced dose in cortical bone (in Gy/Bq)

x (mm)	^{177}Lu	^{90}Sr	^{153}Sm	^{131}I	^{137}Cs	^{201}Au
0.01	9.683E+05	9.342E+05	1.263E+06	1.430E+06	2.026E+06	1.151E+06
0.05	3.868E+04	3.732E+04	5.046E+04	5.711E+04	8.093E+04	4.597E+04
0.1	9.655E+03	9.316E+03	1.260E+04	1.425E+04	2.020E+04	1.148E+04
0.5	3.812E+02	3.680E+02	4.975E+02	5.629E+02	7.978E+02	4.535E+02
1	9.377E+01	9.056E+01	1.224E+02	1.385E+02	1.963E+02	1.116E+02
5	3.295E+00	3.195E+00	4.321E+00	4.878E+00	6.916E+00	3.954E+00
10	7.008E−01	6.833E−01	9.240E−01	1.040E+00	1.476E+00	8.494E−01

and 2, k and T are outgoing photon and incident electron energies respectively. The Bremsstrahlung cross-section values decreases with the increase in the electron energy. The maximum energy, Bremsstrahlung energy, Bremsstrahlung number and energy yield of the beta isotopes used in the present study are given in the Table 1. The evaluated Bremsstrahlung spectra employed in the dose calculations are shown in Figures 3-8. These figures show that shapes of Bremsstrahlung spectra, which indicates the maximum and minimum Bremsstrahlung yield corresponds to their energy. Hence, the presented data provides a quick and convenient reference for radiation protection. Bremsstrahlung production is higher in bone than that of muscle. The shape of the Bremsstrahlung spectrum depends on the corresponding beta spectrum. Calculated values of absorbed dose (in Gy/MBq) due to Bremsstrahlung radiation for bone and muscle shown in Tables 2-7. These tables show that absorbed dose of Bremsstrahlung of bone and muscle decreases with the

Table 3: Evaluated beta induced dose in cortical bone(in Gy/Bq)

x (mm)	^{165}Dy	^{99}Mo	^{89}Sr	^{59}Fe	^{32}P	^{166}Ho
0.01	1.078E+06	1.226E+06	8.998E+05	2.847E+06	7.229E+05	9.951E+05
0.05	4.305E+04	4.899E+04	3.595E+04	1.137E+05	2.888E+04	3.976E+04
0.1	1.075E+04	1.223E+04	8.974E+03	2.838E+04	7.210E+03	9.925E+03
0.5	4.246E+02	4.831E+02	3.547E+02	1.120E+03	2.851E+02	3.922E+02
1	1.046E+02	1.189E+02	8.734E+01	2.755E+02	7.024E+01	9.659E+01
5	3.704E+00	4.204E+00	3.099E+00	9.660E+00	2.502E+00	3.427E+00
10	7.964E−01	9.013E−01	6.677E−01	2.049E+00	5.415E−01	7.380E−01

Table 4: Evaluated beta induced dose in cortical bone(in Gy/Bq)

x (mm)	^{92}Sr	^{188}Re	^{90}Y	^{147}Pr	^{60}Co	^{42}K
0.01	3.267E+06	9.291E+05	7.577E+05	1.246E+06	2.862E+06	6.221E+05
0.05	1.305E+05	3.712E+04	3.027E+04	4.978E+04	1.143E+05	2.485E+04
0.1	3.258E+04	9.266E+03	7.557E+03	1.243E+04	2.854E+04	6.205E+03
0.5	1.287E+03	3.662E+02	2.987E+02	4.912E+02	1.126E+03	2.453E+02
1	3.165E+02	9.021E+01	7.358E+01	1.210E+02	2.769E+02	6.045E+01
5	1.114E+01	3.204E+00	2.616E+00	4.296E+00	9.689E+00	2.154E+00
10	2.375E+00	6.912E−01	5.649E−01	9.262E−01	2.050E+00	4.665E−01

Table 5: Evaluated beta induced dose in cortical muscle (in Gy/Bq)

x (mm)	^{177}Lu	^{90}Sr	^{153}Sm	^{131}I	^{137}Cs	^{201}Au
0.01	2.486E+07	2.177E+07	2.947E+07	3.490E+07	4.888E+07	2.499E+07
0.05	9.938E+05	8.701E+05	1.178E+06	1.395E+06	1.954E+06	9.989E+05
0.1	2.482E+05	2.173E+05	2.942E+05	3.485E+05	4.880E+05	2.495E+05
0.5	9.860E+03	8.632E+03	1.169E+04	1.384E+04	1.938E+04	9.911E+03
1	2.443E+03	2.139E+03	2.896E+03	3.430E+03	4.804E+03	2.456E+03
5	9.112E+01	7.979E+01	1.080E+02	1.279E+02	1.792E+02	9.162E+01
10	2.087E+01	1.828E+01	2.474E+01	2.930E+01	4.104E+01	2.099E+01

Table 6: Evaluated beta induced dose in cortical muscle (in Gy/Bq)

x (mm)	^{165}Dy	^{99}Mo	^{89}Sr	^{59}Fe	^{32}P	^{166}Ho
0.01	2.318E+07	2.768E+07	1.873E+07	7.675E+07	1.382E+07	2.089E+07
0.05	9.266E+05	1.106E+06	7.488E+05	3.068E+06	5.525E+05	8.352E+05
0.1	2.314E+05	2.763E+05	1.870E+05	7.663E+05	1.380E+05	2.086E+05
0.5	9.193E+03	1.098E+04	7.429E+03	3.044E+04	5.482E+03	8.286E+03
1	2.278E+03	2.720E+03	1.841E+03	7.543E+03	1.359E+03	2.054E+03
5	8.499E+01	1.015E+02	6.868E+01	2.812E+02	5.069E+01	7.661E+01
10	1.947E+01	2.324E+01	1.574E+01	6.440E+01	1.162E+01	1.755E+01

Table 7: Evaluated beta induced dose in cortical muscle (in Gy/Bq)

x (mm)	^{92}Sr	^{188}Re	^{90}Y	^{147}Pr	^{60}Co	^{42}K
0.01	8.039E+07	1.899E+07	1.522E+07	2.562E+07	8.055E+07	1.187E+07
0.05	3.213E+06	7.593E+05	6.085E+05	1.024E+06	3.220E+06	4.745E+05
0.1	8.026E+05	1.896E+05	1.520E+05	2.558E+05	8.042E+05	1.185E+05
0.5	3.188E+04	7.533E+03	6.037E+03	1.016E+04	3.194E+04	4.708E+03
1	7.901E+03	1.867E+03	1.496E+03	2.518E+03	7.916E+03	1.167E+03
5	2.946E+02	6.965E+01	5.582E+01	9.394E+01	2.951E+02	4.353E+01
10	6.748E+01	1.596E+01	1.279E+01	2.152E+01	6.758E+01	9.975E+00

distance in the target medium. For example, injection of I-131 induce Bremsstrahlung dose 138.5 Gy/Bq at 1 mm from injected place [From Table 2], which is not negligible. Similarly, we can analyze Bremsstrahlung dose for other nuclides also. Hence, the results showed that Bremsstrahlung dose may not always be negligible with in few mm of the target thickness and in such cases Bremsstrahlung component should be included in the dosimetric calculations of beta therapy.

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