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A dosimetric study of Beta induced bremsstrahlung in bone

H.C. Manjunatha

Department of Physics, Government College for Women, Kolar, Karnataka, India

HIGHLIGHTS

- The beta-induced bremsstrahlung spectra produced by 113 pure beta nuclides in the bone are computed.
- The spectral shapes are intended to provide a quick and convenient reference for radiation dosimetry.
- The absorbed bremsstrahlung dose in bone is also computed.
- The evaluated beta bremsstrahlung dose as a function of distance and nuclides is also studied.

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ABSTRACT

A dosimetric study of beta-induced bremsstrahlung in bone is important in the field of radiation protection. The beta-induced bremsstrahlung spectra produced by 113 pure beta nuclides in the bone are computed. The spectral shapes are primarily responsible for variations in the shapes by depth-dose distributions. They are intended to provide a quick and convenient reference for spectral shapes and to give an indication of the wide variation in these shapes. The computed bremsstrahlung spectrum is used in the evaluation of bremsstrahlung dose in bone. The evaluated beta bremsstrahlung dose as a function of distance for the studied nuclides is also presented. The beta bremsstrahlung dose decreases with the increase in distance. Present work also estimates the dosimetric parameters of bremsstrahlung such as yield, intensity and dose rate of bremsstrahlung by various pure beta nuclides in tissues of human skeleton such as cortical bone, red marrow, yellow marrow, spongiosa and cartilage. The yield, intensity and dose rate of bremsstrahlung in the cortical bone are higher than that of red marrow, yellow marrow, spongiosa and cartilage. Hence cortical bone is more beta/bremsstrahlung radiosensitive than that of other tissues of human skeleton. The estimated bremsstrahlung efficiency, intensity, photon spectra and photon track-length distributions determine the quality and quantity of the radiation. Precise estimation of this source term is very important in planning for radiotherapy and diagnosis.

1. Introduction

Beta-emitting nuclides are used in the treatment of both malignant and non-malignant conditions. In malignant conditions tumor specific metabolic and biological characteristics are effectively deployed to optimize the targeting radionuclides and hence permit the successful therapy. A therapeutic radionuclide should emit principally non-penetrating radiations to maximize self-irradiation of the target region and minimize irradiation of non-target regions. Increasingly, pure b-ray emitters are being considered and used as therapeutic radionuclides (Fritzberg and Wessels, 1995). In the instances where beta-emitting radionuclides are used for therapy of non-malignant conditions, the specific area of current interest relates to application of radionuclides in radiosynovectomy. This includes the treatment of subtle painful conditions associated with disease of joints such as rheumatoid arthritis or villonodular synovitis (Franssen et al., 1989; Vont Pad Bosch et al., 1981). Beta-emitting nuclides such as ^{90}Y, ^{32}P, ^{165}Dy etc. offer clinically proven and cost effective alternative to surgical synovectomy (Rodrigues-Merchan et al., 1997; Lofquist et al., 1997). Uchiyama et al. (1997) reported that Strontium-89 chloride is being widely used as a palliative treatment for patients with bone pain caused by bone metastases. The radionuclides such as ^{89}Sr and ^{32}P 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 ^{90}Y appears to be a potential beta-emitting radionuclide, which has been shown to offer attractive considerations for being used in radioimmunotherapy (Stewart et al., 1988). Beta-emitting radionuclide like ^{32}P also finds application in infusional brachytherapy (Hien et al., 1997).

The diagnosis of bone metastases can be made using several diagnostic imaging techniques. The most utilized technique is the ^{99m}Tc nuclear medicine bone scan; the radionuclide tracer, attached

E-mail address: manjunathhc@rediffmail.com

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to an organophosphate (methylene diphosphonate), is specifically incorporated into the skeleton in areas of significant osteoblast activity, preferentially binding to hydroxyapatite within the bone matrix (Tomblyn, 2012). Beta emitting nuclides such as ^{32}P, ^{89}Sr, ^{153}Sm, ^{186}Re, ^{117m}Sn and ^{177}Lu are bone-seeking radiopharmaceutical agents which have shown evidence of safety and efficacy in the medical literature. These beta emitters release highly energetic electrons that deposit their energy over up to several millimeters in the surrounding tissues. The energies of emitted beta particles are generally not sufficient to elicit a significant cytotoxic response (Tomblyn, 2012). Beta emitters such as ^{89}Sr, ^{153}Sm and ^{177}Lu are used in the treatment of skeletal metastases (Taylor, 1994; Dolezal, 2000, Srivastava et al., 1998). Hough et al. (2011) formulated the comprehensive electron dosimetry model of the adult male skeletal tissues. Lee et al. (2006) evaluated the absorbed dose per incident photon fluence to these skeletal regions from idealized parallel beams of monoenergetic photons using the paired-image radiation transport model.

The incorporated therapeutic beta emitting nuclides produce bremsstrahlung radiation and could have different energies and intensities. The bremsstrahlung yield is a function of two components, namely internal bremsstrahlung and external bremsstrahlung. Bremsstrahlung is produced when charged particles are accelerated in the Coulomb field of nuclei. In the case of beta particles, a distinction has to be made between the radiation produced by the beta particle in the field of its parent nucleus and that produced in the field of external nucleus. The former is called internal bremsstrahlung (IB) and the latter is external bremsstrahlung (EB). The intensity of EB largely depends on the energy of the emitted beta particles and atomic number of the surrounding matrix material. On the other hand, IB component inherently depends on the interaction of the emitted beta particle with the nucleus of the source radionuclide itself. It can therefore be stated that the photon characteristics of EB depend on the surrounding matrix material (tissue), whereas, those of IB would depend on the emission characteristics of radionuclide. 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. The radiation therapy needs experimental evidence on the dosimetric studies of bremsstrahlung radiation. But these experiments are very difficult to undertake and analyze, since many biochemical effects are taking place at the same time, competing with radiation effects. The resulting hazard of bremsstrahlung radiation released during beta therapy may therefore be of some concern, at least theoretically, and should be evaluated. A radiation dose analysis is also fundamental to the use of either diagnostic or therapeutic radiopharmaceuticals. The phenomenon of bremsstrahlung production is most important at high energies and high medium atomic numbers (Turner, 1986). The objectives of the present work are to compute the bremsstrahlung dosimetric parameters in bone such as beta-induced bremsstrahlung spectrum and absorbed dose. Present work also estimates the dosimetric parameters of bremsstrahlung such as yield, intensity and exposure rate of bremsstrahlung by various pure beta nuclides in tissues of human skeleton such as cortical bone, red marrow, yellow marrow, spongiosa and cartilage. The objective of the work is to estimate the spectrum, dose, efficiency (yield) and exposure of bremsstrahlung induced by beta nuclides in bone.

1.1. Estimation of EB cross section

Markowicz and VanGriken (1984) proposed an expression for modified atomic number (Z_{mod}) of compound target defined for bremsstrahlung process to take into account the self absorption of bremsstrahlung and electron back scattering.

$$\text{Here, } Z_{mod} = \frac{\sum_i^l (W_i Z_i^2/A_i)}{\sum_i^l (W_i Z_i/A_i)} \lim^{x\to\infty} \quad (1)$$

Here, W_i, A_i and Z_i are the atomic weight, weight fraction and atomic number of ith element respectively. l in the equation represents number of elements in that mixture (bone). The six elements whose atomic numbers are chosen adjacent to that of the bone (Z_{mod} = 10.2509) are N, O, F, Ne, Na, Mg and their Z values are 7, 8, 9, 10, 11, 12 respectively. Z_{mod} is evaluated using Eq. (1) and their composition (ICRU-44). The EB cross section for bone is evaluated using Lagrange's interpolation technique (Seltzerand Berger, 1986); theoretical EB cross section data are given for elements using the following expression:

$$\sigma_{Z_{mod}} = \sum \left(\frac{\prod_{Z' \neq Z} (Z_{mod} - Z)}{\prod_{z \neq Z} (z - Z)} \right) \sigma_z \quad (2)$$

where lower case z is the atomic number of the element of known EB cross section σ_z adjacent to the modified atomic number (Z_{mod}) of the compound whose EB cross section $\sigma_{Z_{mod}}$ is desired and upper case Z are atomic numbers of other elements of known EB cross section adjacent to Z_{mod}. The estimated $\sigma_{Z_{mod}}$ (milli barn/MeV) is used for evaluation of spectrum. The evaluated $\sigma_{Z_{mod}}$ as a function of electron energy is shown in Fig. 1.

1.2. Evaluation of bremsstrahlung spectrum

The number $n(T, k)$ of EB photons of energy k when all of the incident electron energy T is completely absorbed in the thick target is given by Bethe and Heitler (1934) and is

$$n(T, k) = N \int_k^T \left(\frac{\sigma(E, k)}{(-dE/dx)} \right) dE \quad (3)$$

where $\sigma(E, k)$ is the 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

$$S(k) = \frac{\int_T^{T_{max}} n(T, k)\, P(T)\, dT}{\int_T^{T_{max}} P(T)\, dT} \quad (4)$$

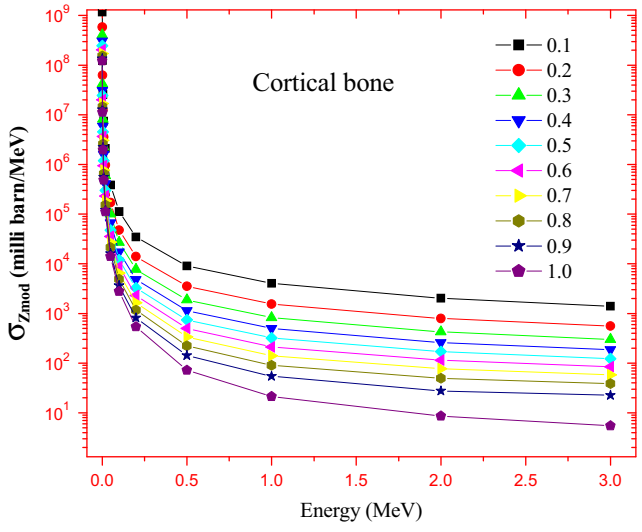

Fig. 1. Variation of bremsstrahlung cross section with photon energy in the cortical bone.