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Determination of age specific ^{131}I *S*-factor values for thyroid using anthropomorphic phantom in geant4 simulations

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HIGHLIGHTS

- Using anthropomorphic phantom, β- and γ-rays absorbed fractions are found for I-131.
- It was done for thyroid of various age groups and geometrical models with Geant4.
- For β-particles, absorbed fraction increased from 0.88 to 0.97 with fetus age.
- The max. difference in absorbed energy per decay for soft tissue is 7.2% for γ-rays and 0.4% for β-particles.
- Two-lobe ellipsoidal model shows 3% lower value of *S*-factor than the ORNL data.

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ABSTRACT

Using anthropomorphic phantom in Geant4, determination of β- and γ-absorbed fractions and energy absorbed per event due to ^{131}I activity in thyroid of individuals of various age groups and geometrical models, have been carried out. In the case of ^{131}I β-particles, the values of the absorbed fraction increased from 0.88 to 0.97 with fetus age. The maximum difference in absorbed energy per decay for soft tissue and water is 7.2% for γ-rays and 0.4% for β-particles. The new mathematical MIRD embedded in Geant4 (MEG) and two-lobe ellipsoidal models developed in this work have 4.3% and 2.9% lower value of *S*-factor as compared with the ORNL data.

1. Introduction

Radioactive Iodine is taken up by the thyroid from the main bloodstream quite quickly. The source of this radionuclide in thyroid could be a medical procedure for the treatment of hyperthyroidism or intake from an accidental release from a nuclear facility etc. In nuclear accidents, amongst other radioactive isotopes, various isotopes of iodine are released in significant proportions in the environment (WHO, 1999). It has been estimated that the risk of an accident in a nuclear facility cannot be eliminated completely (Sovacool, 2011). Consequently, it is very important to study the dosimetry protocols, set for radioiodine intake, on the basis of a broad spectrum of population parameters including age, gender, mass of thyroid, etc. (Krajewski et al., 2008). This may allow a reliable estimation of the absorbed dose and subsequently an adequate contingency plan for the population at risk during a nuclear accident. Precise estimation of absorbed dose is also extremely important, to determine the risk versus benefit ratio, during radiotherapy treatments.

The most popular methodology for dosimetry of internally administered radionuclides is the Medical Internal Radiation Dose (MIRD) schema. This system of dose calculation provides a systematic approach towards combining biological distribution data, clearance and physical properties of radionuclides in order to estimate the internal doses. The standard MIRD schema assumes a uniform deposition of activity and distribution of radiation energy within the target volume. However more advanced schema considers the non-uniform and microscopic (i.e. cellular level) distribution of radioactivity (Zanzonico, 2000). The MIRD schema defines a parameter called *S*-factor (mean absorbed dose per unit cumulative

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activity) which is associated with the fraction of radiation energy absorbed per unit mass inside the target volume. The *S*-factors values have been shown as the most sensitive parameter in dosimetry models for iodine ingestion and inhalation (Harvey et al., 2003; Harvey et al., 2006). The methodology for the inclusion of non-uniformities and dose in-homogeneities cellular and Voxel based *S*-factors has been defined by the MIRD committee and several other authors (Bolch et al., 1999; Goddu et al., 1997; Sgouros et al., 2010). The correct estimation of the *S*-factors requires an accurate knowledge of the biological distribution of radiopharmaceutical as well as the mass of the target organ.

Although imaging based computational codes for dosimetry such as SIMDOS (Stabin, 2006), RTDS (Liu et al., 1999), RMDP (Guy et al., 2003) etc., are available. It is still not practical to calculate the absorbed fractions (and consequently the *S*-factors) for a diverse range of sizes and shapes of the target volumes especially in the case of thyroid treatment. The Monte Carlo simulations, being capable of handling complex geometries, are well suited to this task (Stabin and Flux, 2007). For this purpose various research groups have developed anthropomorphic phantoms that use the tissue composition and densities defined by ICRP (Cristy and Eckerman, 1987; Snyder et al., 1978; Snyder et al., 1969). These phantom models use spheres, cylinders and cones etc., also incorporating the age as a factor in determining the size of the organs. Regular geometry shapes (sphere, cylinders etc.,) provide a good approximation for the absorbed fraction calculations. However there is always a need for more accurate models that can represent correctly, the size and shape of the organ.

The values of *S*-factor for ^{131}I includes both β- and γ- contributions. The S-factors are generally tabulated for adult thyroids having standard sizes of body and organs. But for thyroid Grave's disease, patients have a range of values of thyroid sizes. Previous research (Traino et al., 2005) suggested a scaling law for penetrating and non-penetrating radiation to incorporate the adjustment in calculations for a size of an organ different from the standard. This scaling law, however, is an over-approximation for Ellipsoidal organs (Hansson, 2012). In this study we estimated the *S*-factor values for ^{131}I in thyroid of individuals of both genders in various age groups, using Geant4 Monte Carlo simulation tool (Agostinelli et al., 2003; Allison et al., 2006). The provision has also been made to estimate the *S*-factors for Graves's disease with patients having variable thyroid sizes (Muhammad et al., 2008). A comparison has been carried out in this work for the *S*-factors calculated using various thyroid geometries including spherical and ellipsoidal with published data. In order to represent the thyroid organ precisely, the two lobes ellipsoidal model is also presented along-with single lobe ellipsoidal model. A new mathematical model incorporating anthropomorphic phantom with MIRD Embedded in Geant4 (MEG) for thyroid is also presented here for the estimation of absorbed dose factors. The results of new model MEG are compared with corresponding values obtained with ORNL phantom and published data (Geant4_Collaboration, 2012).

The absorbed fractions for electrons and photon distributed uniformly in the ellipsoidal thyroid model are presented, covering an energy range 0.1–4 MeV in case of electrons and 0.02–2.75 MeV in case of γ-ray photons. This energy range was adopted so that the *S*-factors for various isotopes of iodine currently employed in nuclear medicine procedures or any accidental inhalation and injections can be estimated. The ICRP soft tissue and water, have been employed to estimate the energy deposition per decay both for γ- photons and β- particles.

2. Materials and methods

For absorbed dose calculation we used the MIRD schema approach that can be represented as (Bolch et al., 2009; Watson et al., 1993):

$$D(r_T) = S(r_T \leftarrow r_s)\tilde{A}(r_s), \tag{1}$$

Where $T = S =$ Thyroid; $D(r_T)$ is the mean absorbed dose per unit cumulative activity and $\tilde{A}(r_s)$ is the cumulative activity in the thyroid organ. The *S*-factor is a characteristic of type of radionuclide, target size and target source configuration and is define as (Bolch et al., 2009; Loevinger and Berman, 1968):

$$S(r_T \leftarrow r_s) = \frac{1}{M(r_T)} \sum_i y_i E_i \phi(r_T \leftarrow r_s,\ E_i) \tag{2}$$

where $M(r_T)$ is the mass of the target (kg); y_i is number of radiations with energy E_i(MeV) emitted per nuclear transition; $\phi(r_T \leftarrow r_s, E_i)$is the fraction of energy emitted by the source and absorbed in the target region. This quantity is usually calculated using the Monte Carlo simulations using (Loevinger and Berman, 1968):

$$\phi(\mathrm{r_T} \leftarrow r_s, E_i) = E_{dep}/E_{total} \tag{3}$$

where E_{dep} is the total energy deposited in the target region per disintegration and E_{total} is the total energy emitted from source region per disintegration. The absorbed fractions from γ-rays and β-particles can be calculated separately using the Monte Carlo simulations and then summed to compute *S*-factor (mGy Bq^{-1} s^{-1}) as follows:

$$S(r_T \leftarrow r_s) = (1.602 \times 10^{-10}/M(r_T)) \sum_i \{y_i(\gamma)E_i(\gamma)\phi_\gamma(r_T \leftarrow r_s, E_i) + y_i(\beta)E_i(\beta)\phi_\beta(r_T \leftarrow r_s, E_i)\} \tag{4}$$

where the factor 1.602×10^{-10} converts MeV into joules.

For Monte Carlo simulations we have used Geant4 in this study. A key feature of Geant4 is that it offers various low energy physics models such as PENELOPE and LIVERMORE for accurate simulation of low energy photons and electrons. The accuracy of Geant4 and comparison of the physics models has been investigated by several groups (Amako et al., 2005; Kadri et al., 2005; Poon and Verhaegen, 2005). The energy deposition in our simulation was scored by utilizing *GetEnergyDeposit*( ) method of Geant4.9.6 classes. With the *GetPosition*( ) method the particle position was tracked in the target area. If the particle remained inside target the energy was scored by *GetEnergyDeposit*() method. The energy deposited (E_i) and its square (E_i^2) for *i*th event was scored in the *EventAction* class and these results were summed by the *RunAction* class for total energy deposition in the target. An average value was calculated for the *N* number of particles simulated. The square term was used for the estimation of statistical standard deviation (Geant4_Collaboration, 2012).

The absorbed fractions for electrons and γ-rays distributed uniformly in ellipsoidal shaped thyroid were estimated by considering the average energy of both the γ-rays and β- particle emitted from a particular radioisotope of iodine. However we consider a range of average energies of β-particles and γ-rays so that most of the isotopes of iodine (^{123}I, ^{124}I, ^{125}I, ^{131}I, ^{132}I, ^{135}I) are accounted for. For this purpose, the range of average energies considered for β-particles was 0.1–4 MeV and that for the γ-rays was 0.02–2.75 MeV (ICRP-38, 2008). The absorbed fraction for each particle energy was estimated by energy deposition in a target by taking principle axes 1/1/2 for ellipsoid in this work. In this work, for absorbed fraction calculations (ICRP-89, 2001), the ICRP soft tissue composition, with density 1.05×10^3 kg/m^3 has been employed. These absorbed fractions were considered for various age groups including developing fetus, newborn baby, one, five, ten, fifteen years and adult individuals. For these individuals the mass of thyroid varies in 2×10^{-5}–0.15 kg range.

The results of S-factors calculations are affected by the degree of detail included in the model compared with the original