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To Study the Activity of Few Radionuclides Using Biokinetic Model

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Abstract:

Activity of the radionuclides and the doses because of sharp intake of 1 Bq of a long lived radionuclide (^{133}Ba) and a short lived radionuclide (^{99m}Tc) have been calculated based on the human alimentary tract model (HATM) through ingestion. Due to ingestion maximum radiation dose is deposited in the alimentary tract, which consists of seven tissue compartments, e.g., Oral Cavity (OC), Esophagus (OP), Stomach (ST), Small Intestine (SI), Left Colon (LC), Right Colon (RC) and Rectosigmoid Colon (RSC). The radiation dose deposited in 2 of the organs within the tract, e.g., ST, SI and 3 other organs outside of the tract, e.g., liver, right lung (RL) and left lung (LL) are considered. Tissue masses of alimentary tract for Bangladeshi people of different age groups were taken for the calculation. The age groups are such as new born, 1 yr, 10 yrs, adult male, adult female for the first type considering 2 organs and <20 yrs male, 21-40 yrs male, 41-60 yrs male, > 60 yrs male, <20 yrs female, 21-40 yrs female, 41-60 yrs female for the rest 3 organs. The time required to get an insignificant value of activity depends more on decay constant of the radionuclides than the rate constant of the organs. The activity values became insignificant approximately after 5 hrs, 8 hrs, 60 hrs and 90 hrs in ST, SI respectively for long lived radionuclide. These time values are relatively shorter for short lived radionuclide than those for other radionuclides.

Keywords: *Activity of the radionuclide, acute intake, biokinetic modeling, human alimentary tract model (HATM).*

Introduction

The universe is intimately entangled with radiation which is a form of energy present all around us. This energy spreads in the form of particles or electromagnetic rays that are given off by excited atoms or nuclei. Three different kinds of ionizing radiations, namely alpha and beta particles and gamma rays are emitted from various natural and man-made radionuclides. The present work is concerned with one from this list, more specifically the gamma radiation that can carry enough energy and is assumed to have positioned inside human body. Gamma rays can ionize atoms in, the tissue atoms are ionized by gamma rays directly that are called "secondary ionization". Transferring energy from gamma rays to atomic particles creates ionizations. The energy gained particles interact with tissue to form ions via secondary ionizations.

The biological effects of ingested radionuclides depend greatly on the activity, the bio-distribution, and their removal rates, which in turn depends on its chemical form, the particle size, and route of entry. Radionuclides incorporated in the human body irradiate the tissue over time periods determined by their physical half-lives and their biological retention within the body. The International Commission on Radiological Protection (ICRP) predicts that an effective dose of one sievert carries a 5.5% chance of developing cancer. Internally deposited radionuclides emit ionizing radiations such as alpha particles, beta particles and gamma rays. Barium-133 and Technetium-99 give gamma emissions which are discussed in the research. Technical details and advice on the assessment of internal contamination by direct methods has been published by the IAEA (1989).

The ICRP recommends about the methods for the assessment of the intake of radionuclides, and the resulting doses are got from monitoring data (ICRP, 1996a; ICRP, 1996b). The biologic effects of radionuclide therapy are mediated via a well-defined physical quantity, the absorbed dose, which is defined as the energy absorbed per unit mass of tissue.

In Publication 26, the ICRP (1979a) introduced the use of (tissue) weighting factors Iv_y to calculate the committed effective dose equivalent from individual tissue dose equivalents. This provides a common way of expressing doses from external radiation, "which are relatively uniform to all body tissues, and from intakes of radionuclides, which can be very heterogeneous. The ICRP applied this advice in the various parts and supplements of its Publication 30, which described the biokinetic models used for calculating dose equivalents to organs and tissues from intake by inhalation and ingestion of a wide range of radionuclides in different chemical forms (ICRP, 1979a; ICRP, 19781; ICRP, 1982; ICRP, 1979b).

Biokinetic modelling of retention and biophysical modelling of energy deposition may still be needed to calculate the intake and the committed effective dose. Direct measurements are useful in qualitative as well as quantitative determinations of radionuclides in a mixture that might have been inhaled, ingested or injected. The identification of the mode of intake by measuring the activity distribution is assisted by direct measurements (Watson& Ford, 1980; Harrison, 2015). Sequential measurements, where they are possible, can reveal the redistribution of activity and give information about the total body retention and the biokinetic behaviour of radionuclides in the body. The Safety Guide has been described for various types of reference levels (IAEA, 1996). The ICRP has published Biokinetic models for most radionuclides based on Referring Man (1975). and the observed behavior of radionuclides in humans and animals.

The HATM

The human alimentary tract model (HATM) is a new model that can replace the model for the gastrointestinal tract taken by ICRP in Publication 30. The HATM works through four territories of the tract such as small intestine, upper large intestine, lower large intestine & stomach.

Information has become available on the location of sensitive cells and retention of radionuclides in different regions of the alimentary tract. The 1990 recommendations of ICRP introduced specific risk estimates and tissue weighting factors, W_T, for radiation-induced cancer of the esophagus, stomach and colon, requiring dose estimates for each of these regions.

Methodology

The submitted research has been incorporated with the compartmentalized form of the HATM. The calculations need enough biological as well as radiological data to prepare a data library with the help of Microsoft Access 7.0 program. Radioisotopes with half-life, decay constant, and like these type of data are recorded in the library.

The rate at which any radioactive substance decays with time is called activity. The International System (SI) unit for activity is the Becquerel (Bq), which is that quantity of radioactive material in which one atom transforms per second. The Becquerel is a small unit. In practical situations, radioactivity is often quantified in kilobecquerels (kBq) or megabecquerels (MBq). The curie (Ci) is also commonly used as the unit for activity of a particular source material.

The equation of activity is given as

$$\frac{d}{dt}A_i(t) = -\lambda_i A_i(t) - \lambda_R A_R(t) + I(t) \qquad (1)$$

Here,
$A_i(t)$ = Activity of the radionuclide.
A_i = Activity of the organ i (i=1,2,3,……7)
λ_i = Transfer rate of the radionuclide comparing to organ i.
λ_R = Decay constant.
$I(t)$ = Initial activity

Now we may get four different equations for four organs equation (1). These are shown below.

For oral cavity

$$\frac{d}{dt}A_{OC}(t) = -\lambda_{OC}A_{OC}(t) - \lambda_R A(t) + I(t). \qquad (2)$$

For esophagus

$$\frac{d}{dt}A_{OP}(t) = -\lambda_{OP}A_{OP}(t) - \lambda_R A_{OP}(t) + \lambda_{OC}A_{OC}(t) \qquad (3)$$

For stomach

$$\frac{d}{dt}A_{ST}(t) = -\lambda_{ST}A_{ST}(t) - \lambda_R A_{ST}(t) + \lambda_{OP}A_{OP}(t) \qquad (4)$$

For small intestine

$$\frac{d}{dt}A_{SI}(t) = -\lambda_{SI}A_{SI}(t) - \lambda_R A_{SI}(t) - \lambda_B A_{SI}(t) + \lambda_{ST}A_{ST}(t) \qquad (5)$$

Where,
λ_R = Decay constant
λ_{OC} = Constant rate for the loss from oral cavity,
λ_{EP} = Constant rate for the loss from esophagus,
λ_{ST} = Constant rate for the loss from stomach,
λ_{SI} = Constant for the loss from small intestine,

Table 1 represents the values of λ_{OC}, λ_{EP}, λ_{ST}, λ_{SI}. A_{OC}, A_{EP}, A_{ST}, A_{SI} represent the activity in OC, EP, ST, SI respectively.

H. Bateman's equation gives the solution of the equation (NCRP, 1980) as

$$A_i = N_o \sum_{i=1}^{n} C_i e^{-\lambda_i t}$$

$$= N_o\,[C_1\exp(-\lambda_1 t) + C_2\exp(-\lambda_2 t) + \ldots\ldots\ldots + C_n\exp(-\lambda_n t)] \qquad (6)$$

Table 1. Constant Rate for Different Parts of a HAT

Name of the Organs	Mean residence time	Constant rate (/d)
1. Oral Cavity	12 sec	7200
2. Esophgus	40 sec	2160
3. Stomach	70 min	20.57
4. Small intestine	4 hrs	6

Where

$$C_m = \frac{\prod_{i=1}^{n} \lambda_i}{\prod_{i=1}^{n} (\lambda_i - \lambda_m)}$$

$$= \frac{\lambda_1 \lambda_2 \lambda_3 \ldots\ldots\ldots\lambda_n}{(\lambda_1 - \lambda_m)(\lambda_2 - \lambda_m)(\lambda_3 - \lambda_m)\ldots\ldots\ldots\ldots(\lambda_n - \lambda_m)} \quad (7)$$

The activity for oral cavity A_1 (t) is got by placing i = 1 into equation (6)

$$A_1 = N_o e^{-\lambda_1 t} \quad (8)$$

For the second compartment the value of activity can be obtained by putting i=2 into equation (6)

$$A_i = N_o \sum_{i=1}^{n} C_i e^{-\lambda_i t}$$

$$A_2 = N_o \left(C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t} \right);$$

And equation (7) gives

$$C_m = \frac{\prod_{i=1}^{n} \lambda_i}{\prod_{i=1}^{n} (\lambda_i - \lambda_m)}$$

$$C_m = \frac{\lambda_1 \lambda_2}{(\lambda_1 - \lambda_m)(\lambda_2 - \lambda_m)} \quad [i=2]$$

$$C_1 = \frac{\lambda_1 \lambda_2}{(\lambda_2 - \lambda_1)} \quad [m=1]$$

$$C_2 = \frac{\lambda_1 \lambda_2}{(\lambda_1 - \lambda_2)} \quad [m=2]$$

By putting the values of C_1 C_2 we have

$$A_2 = N_O \lambda_1 \lambda_2 \left(\frac{e^{-\lambda_1} t}{(\lambda_2 - \lambda_1)} + \frac{e^{-\lambda_2} t}{(\lambda_1 - \lambda_2)} \right) \quad (9)$$

For third compartment from the second one, value of activity is got by putting i=3 into equation (6) as

$$A_i = N_o \sum_{i=1}^{n} C_i e^{-\lambda_i t}$$

$$A_3 = N_0 \left(C_1 e^{-\lambda t_1} + C_2 e^{-\lambda_2 t} + C3 e^{-\lambda_3 t_1} \right) \quad [i=3]$$

And Equation (7) now gives

$$C_m = \frac{\prod_{i=1}^{n} \lambda_i}{\prod_{i=1}^{n} (\lambda_i - \lambda_m)}$$

$$C_m = \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_1 - \lambda_m)(\lambda_2 - \lambda_m)(\lambda_3 - \lambda_m)}$$

$$C_1 = \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} \quad [m=1]$$

$$C_2 = \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)} \quad [m=2]$$

$$C_3 = \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)} \quad [m=3]$$

By placing the values of C_1 C_2 C_3 we have

$$A_3 = N_0 \lambda_1 \lambda_2 \lambda_3 \left(\frac{e^{-\lambda_1 t}}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)} + \frac{e^{-\lambda_3 t}}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)} \right) \quad (10)$$

For the fourth compartment the activity is obtained using i=4 into equation (6)

$$A_i = N_o \sum_{i=1}^{n} C_i e^{-\lambda_i t}$$

$$A_4 = N_0 \left(C_1 e^{-\lambda t} + C_2 e^{-\lambda_2 t} + C_3 e^{-\lambda_3 t} + C_4 e^{-\lambda_4 t} \right)$$

And equation (7) gives

$$C_m = \frac{\prod_{i=1}^{n} \lambda_i}{\prod_{i=1}^{n} (\lambda_i - \lambda_m)}$$

$$C_m = \frac{\lambda_1 \lambda_2 \lambda_3 \lambda_4}{(\lambda_1 - \lambda_m)(\lambda_2 - \lambda_m)(\lambda_3 - \lambda_m)(\lambda_4 - \lambda_m)} \quad [i=4]$$

$$C_1 = \frac{\lambda_1 \lambda_2 \lambda_3 \lambda_4}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)(\lambda_4 - \lambda_1)} \quad [m=1]$$

$$C_2 = \frac{\lambda_1 \lambda_2 \lambda_3 \lambda_4}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_2)} \quad [m=2]$$

$$C_3 = \frac{\lambda_1 \lambda_2 \lambda_3 \lambda_4}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)(\lambda_4 - \lambda_3)} \quad [m=3]$$

$$C_4 = \frac{\lambda_1 \lambda_2 \lambda_3 \lambda_4}{(\lambda_1 - \lambda_4)(\lambda_2 - \lambda_4)(\lambda_3 - \lambda_4)} \quad [m=4]$$

Using the values of $C_1\ C_2\ C_3\ C_4$ we got

$$A_4 = N_0\lambda_1\lambda_2\lambda_3\lambda_4\left(\begin{array}{l}\frac{e^{-\lambda_1 t}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)(\lambda_4-\lambda_1)}+\\ \frac{e^{-\lambda_2 t}}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)(\lambda_4-\lambda_2)}+\\ \frac{e^{-\lambda_3 t}}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)}+\\ \frac{e^{-\lambda_4 t}}{(\lambda_1-\lambda_4)(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)}\end{array}\right) \quad (11)$$

For the fifth compartment the activity is obtained using i=5 into equation (6)

$$A_i = N_o\sum_{i=1}^{n} C_i e^{-\lambda_i t}$$

$$A_5 = N_0\left(C_1e^{-\lambda t} + C_2e^{-\lambda_2 t} + C_3e^{-\lambda_3 t} + C_4e^{-\lambda_4 t} + C_5e^{-\lambda_5 t}\right) \quad [i=5]$$

And equation (7) gives

$$C_m = \frac{\prod_{i=1}^{n}\lambda_i}{\prod_{i=1}^{n}(\lambda_i-\lambda_m)}$$

$$C_m = \frac{\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5}{(\lambda_1-\lambda_m)(\lambda_2-\lambda_m)(\lambda_3-\lambda_m)(\lambda_4-\lambda_m)(\lambda_5-\lambda_m)} \quad [i=5]$$

$$C_1 = \frac{\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)(\lambda_4-\lambda_1)(\lambda_5-\lambda_1)} \quad [m=1]$$

$$C_2 = \frac{\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)(\lambda_4-\lambda_2)(\lambda_5-\lambda_2)} \quad [m=2]$$

$$C_3 = \frac{\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)(\lambda_5-\lambda_3)} \quad [m=3]$$

$$C_4 = \frac{\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5}{(\lambda_1-\lambda_4)(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)(\lambda_5-\lambda_4)} \quad [m=4]$$

$$C_5 = \frac{\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5}{(\lambda_1-\lambda_5)(\lambda_2-\lambda_5)(\lambda_3-\lambda_5)(\lambda_4-\lambda_5)} \quad [m=5]$$

By using the values of $C_1\ C_2\ C_3\ C_4\ C_5$ we have

$$A_5 = N_0\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5\left(\begin{array}{l}\frac{e^{-\lambda_1 t}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)(\lambda_4-\lambda_1)(\lambda_5-\lambda_1)}+\\ \frac{e^{-\lambda_2 t}}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)(\lambda_4-\lambda_2)(\lambda_5-\lambda_2)}+\\ \frac{e^{-\lambda_3 t}}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)(\lambda_5-\lambda_3)}+\\ \frac{e^{-\lambda_4 t}}{(\lambda_1-\lambda_4)(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)(\lambda_5-\lambda_4)}+\\ \frac{e^{-\lambda_5 t}}{(\lambda_1-\lambda_5)(\lambda_2-\lambda_5)(\lambda_3-\lambda_5)(\lambda_4-\lambda_5)}\end{array}\right) \quad (12)$$

Results and Discussions

The measure of internal radiation exposure is based on the organ content of a radionuclide at a specific time and over the course of time. Organ content of a radionuclide at a specific time provides an estimate of ionizing radiation dose-rate. The average dose-rate to an exposed organ or tissue is the surrogate for the average organ concentration of the radionuclide and its decay products. Measurements of internally deposited radionuclides at various times after intake therefore provide a pattern of dose-rates as a function of time. In the present work activity of different radionuclides related to internal dosimetry measurements are calculated.
^{133}Ba and ^{99m}Tc radionuclides are all gamma emitting ones. We have calculations on these radionuclides. Here, five organs are considered. The number of divisions for a GI tract is four against five in HATM.

Calculations of Activity for the Ingestion of Radionuclides

Activity of ^{99m}Tc in the Tissues

The activity for different compartments of the HAT has been determined here. Total 5 organs such as liver, left lung (LL), right lung (RL), stomach (ST) and small intestine (SI) are considered here. Some related information is given below:

Among 5 organs of HATM, 2 organs are considered as radionuclide sources. The radionuclides can be moved through the organs directly. The other 3 organs: liver, left lung and right lung act as targets. The age-groups that are thought in consideration for calculations are 1 yr, 10 yrs, adult for first 2 organs. The other organs (3) consider age groups as less than 20 yrs (male and female), 21-40 yrs (male and femal), 41-60 yrs (male and female), and <20 yrs (female). A radionuclide travels through the digestive tract as a result the activity in different compartments increases according to the location of the radionuclide in the tract.

Table 2. Information on activity values arising due to ^{99m}Tc

Name of the compartments	Maximum values	Rising Rate		Falling Rate	
		Magnitude (Bq/hr)	Time span of measurements	Magnitude (Bq/hr)	Time span of measurements
ST	0.88	10.375	0 hr - 0.08 hr	0.55	0.3 hr – 1 hr
SI	0.55	0.49	0 hr – 1 hr	0.08	1.5 hr – 6 hrs

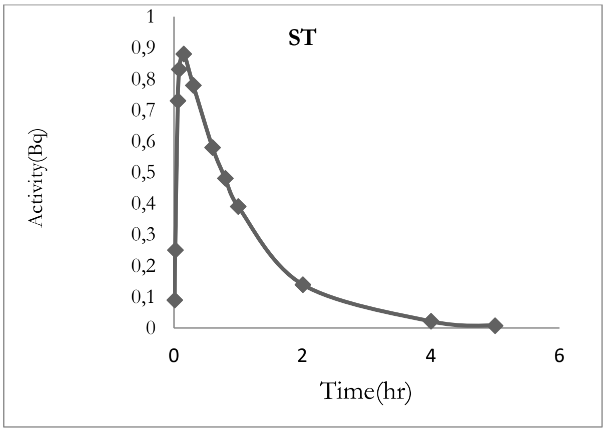

Figure 1. Variation of Activity in ST Due to ^{99m}Tc

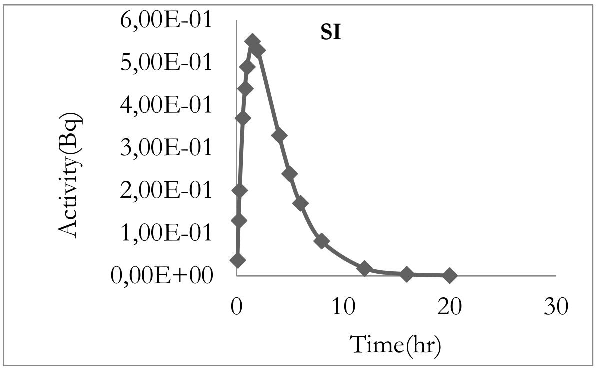

Figure 2. Variation of Activity in SI Due to ^{99m}Tc

Figures 1 and 2 shows the pattern of variation of activity with time while to do calculations for the ^{99m}Tc radionuclide. As of the previous case the maximum value of activity and its rising and falling rates for the radionuclide are given in Table 2.

As of the previous case the rising rate is more than the falling rate – meaning that the time to reach to the peak value of activity in all the compartments is shorter than that to fall. On comparing the magnitude of maximum activity, one would find the compartments to obey the following serial: ST > SI. The time duration of stay in ST is less than that in SI. Time required to reach to an insignificant value of activity is around 5 hrs in case of ST; in SI the value is nearly 16 hrs.

As of the observation made previously for the radionuclide ^{99m}Tc, the time duration of stay is less in ST than that of SI. The time required to reach an insignificant value of activity is 8 hrs in case of ST, in SI this is around 20 hrs.

Activity of ^{133}Ba in the Tissues

Figures 3 to 4 show the pattern of variation of activity arising due to ^{133}Ba in the tissues with time. As of the previous cases the maximum value of activity and its rising and falling rates for the radionuclide are given in Table 3.

Table 3. Information on activity values due to ^{133}Ba

Name of the compartments	Maximum values	Rising Rate		Falling Rate	
		Magnitude (Bq/hr)	Time span of measurements	Magnitude (Bq/hr)	Time span of measurements
ST	0.87	10.375	0 hr - 0.08 hr	0.51	0.44 hr - 0.8 hr
SI	0.26	0.4	0 hr - 0.6 hr	0.09	1.5 hr – 3 hrs

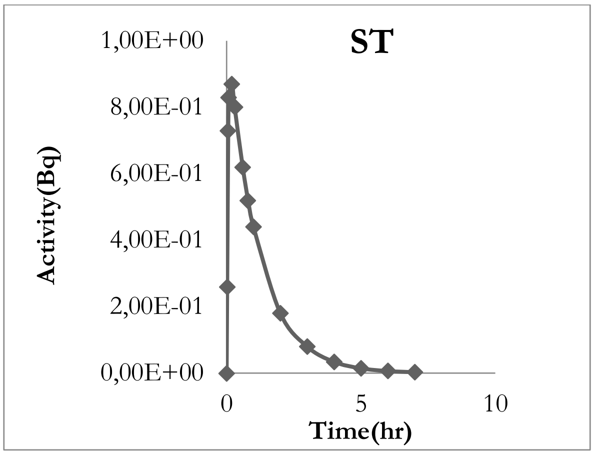

Figure 3. Variation of Activity in ST due to ^{133}Ba

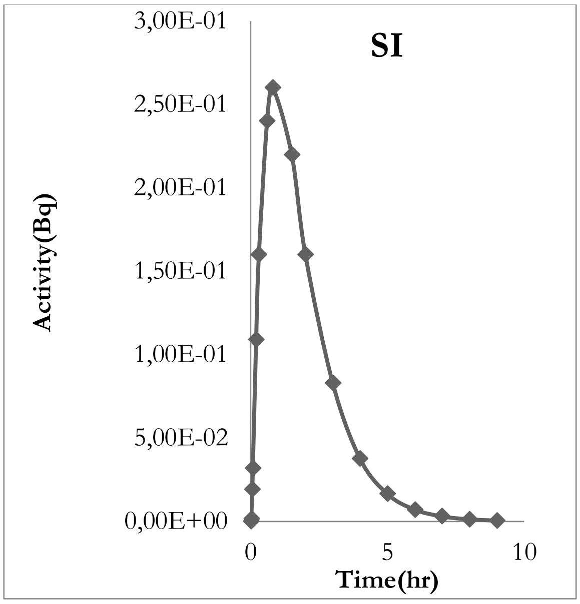

Figure 4. Variation of Activity in SI due to ^{133}Ba

The retention time is less in ST than that of SI. This observation is similar with all the cases mentioned before. The time required to reach to an insignificant value of activity is 5 hrs, 7 hrs respectively for ST and SI.

Conclusions

The important observations could be made from the study. Time required to get an insignificant value of activity in the organs depends more on decay constant of radionuclides than the rate constant of the considered organ. The activity values became insignificant in the work approximately after 5 hrs in ST, 20 hrs in SI for long lived radionuclides such as ^{133}Ba. These time span values are relatively shorter for short lived radionuclides such as ^{99m}Tc than those for the other radionuclides.

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