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Analysis of the Coordinate Transformation in Calculation of the Committed Effective Dose by the Injection of Tc-99m to the Liver

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Abstract

In this study the intravenous injection of Tc-99m which is most widely used in nuclear medicine is considered and the radiation-dose estimation due to this injection is quantitatively analyzed. The main objective of this study is to analyze the effects of coordinate transformation in the liver on the committed effective dose. A phantom (Snyder model) is used which has a simple geometry corresponding approximately to the size and shape of the adult human body and moreover, the Monte Carlo method is used to obtain histories of photons that originate within the source organ. Based on this notion, a program, CAFRA, has been developed which can estimate absorbed fractions in the various organs. The result which pertains to the calculation of the committed effective dose is similar to that of the ICRP Publication 60. Analysis of the coordinate transformation in the calculation of committed effective dose has been accomplished using CAFRA. Conclusively, this programmatic system of analysis provides scientists with a simple tool for the calculation of committed effective dose.

1. Introduction

Today, nuclear energy is widely utilized in various areas such as power supply, agriculture, industry and the application of radionuclides in medicine has led to nuclear medicine which is an area of medicine that diagnoses the condition of human body and treats diseases using radioisotopes.

According to the increase of peaceful uses of nuclear energy, the human being has faced with much chances of exposure to radiation. But the excessive radiation is known as one of the primary factors to induce mutation, cancer, or life shortening so that in case of the diagnosis and therapy of diseases by radionuclides or radiation source it is necessary to correctly predict internal radiation exposure to inhalation, ingestion, or injection of radionuclides. Hence, the mathematical phantom of human body should be given and the computational method should be adopted.

In this study Tc-99m which is most widely used in nuclear medicine is distributed in the liver by intravenous injection and the radiation dose absorbed in the human body owing to the injection is calculated by the application of Snyder model and a program developed using the Monte Carlo method. Then, with the developed program, CAFRA (Calculation of Absorbed FRAction), case study was conducted to estimate the effects of the coordinate transformation. Especially, since the publication of ICRP 60, the domestic radiation protection standards are based on ICRP 60's concepts. Accordingly, the effective dose, radiation weighting factor, tissue weighting factor which are recommended in ICRP 69 have been chosen and calculated in this study.

2. Internal Dose Evaluation Program

2.1 Characteristics of Tc-99m

Tc-99m, compared with other radioisotopes, is produced easily and inexpensively from a generator, so that it takes up a considerably high percentage of the radioisotopes which are used in Korea. Tc-99m emits 0.14 Mev-monoenergetic photons, which are penetrative and easy to collimate. The physical characteristics of Tc-99m are shown in Table 1. In this study, Tc-99m is injected in the form of tagged compound and it can be assumed that all of the injected Tc-99m become uniformly distributed throughout the source organ(liver) without metabolism.

Table 1. The Physical Characteristics of Tc-99m

atomic number	43	
mass number	98.9385	
radiological half life	6 hour	
biological half life	whole body	1 day
	liver	30 days
effective half life	whole body	0.20 day
	liver	0.25 day
origin	the daughter nuclide of Mo^{99}	
manufacturing process	▪ extraction by a physiological saline solution in an ion exchange resin column with Mo^{99}	
critical organ	digestive organ	
others	▪ most stable in the form of TcO_4^- ▪ synthesis of various tagged compounds by simple chemical process	

2.2 Modelling of the Human Body

In this study, one source organ and eight target organs were chosen. The source organ is liver, and the target organs are liver, stomach, small intestine(SI), upper large intestine(ULI), lower large intestine(LLI), lungs, thyroids, and testes. Snyder model is adopted as a mathematical phantom. Simple equations are given for the major body sections and the principal organs. The phantom has a mass of about 70 kg and consists of three types of tissue-lung, skeletal, and other soft tissue. The total-body phantom is made up of three principal sections : (ⅰ) an elliptical cylinder representing the arms, torso, and hips; (ⅱ) two truncated circular cones representing the two legs and feet attached to which is a small region with a plane front surface to approximate the testicles; and (ⅲ) an elliptical cylinder representing the neck region and lower portion of the head, which is topped by half an ellipsoid.

The trunk is a solid elliptical cylinder and includes the arms as well as the pelvis. The volume of the trunk section is 43,982 cm^3 and the mass is 42,701 g. The liver is defined by an elliptical cylinder cut by a plane and has a volume of 1,833 cm^3 and a mass of 1,809 g. The stomach is represented as the mass between two ellipsoids. Its volume is 151.9 cm^3 and its mass is 150 g. The small intestine does not seem to remain in any "standard position" except for the ends, which are relatively fixed. Thus the small intestine is to be regarded as occupying a volume within which it is free to move. This volume, which lies in the pelvic region, is a section of a circular cylinder. Its volume and mass are 1,054 cm^3 and 1,040 g, respectively. The upper large intestine is composed of the ascending colon and the transverse colon. The ascending colon is given by the mass between two circular cylinders and has a volume of 91.22 cm^3 and a mass of 90.02 g. The transverse colon is of elliptical cross section. Its volume is 120.7 cm^3 and the mass is 119.2 g. The lower large intestine consists of the descending colon and the sigmoid colon. The descending colon has a volume of 90.59 cm^3 and a mass of 89.40 g. The sigmoid colon is made up of portions of two torii. The volume of the sigmoid colon is 70.42 cm^3 and the mass is 69.50g. Each lung is half an ellipsoid with an anterior section removed. The volume of both lungs is 3,378 cm^3 and the mass is 999.2 g. The lobes of the thyroid lie between two concentric cylinders and are formed by a cutting surface. Its volume is 19.89 cm^3 and the mass is 19.63 g. The testicles are ellipsoids and have a volume of 37.57 cm^3 and a mass of 37.08 g. The mathematical expression specifying each organ is shown in Table 2.

2.3 Description of Internal Exposure Calculation

The method for calculating the radiation dose to a target organ from a source organ in which a radioisotope is uniformly distributed is based on the concept of absorbed fraction. Absorbed fraction is defined as the fraction of the energy radiated by the source organ which is absorbed by the target organ. When a radioisotope is deposited in a organ, it emits radiation as the source organ and has radiological effects on its neighboring organs as well as the source organ itself. Nonpenetrating radiation, i.e., α radiation or β radiation with short range cannot influence other organs than the source organ itself, whereas penetrating radiation, i.e., photons with long range can affect all organs.

Absorbed fractions are dependent on size, position, composition, and density of the organs, distance between a source organ and target organs, types and energy of radiation, absorbing or scattering material between a source organ and target organs. Absorbed fractions are calculated by applying the Monte Carlo method to the behaviors of photons radiated from the deposited radioisotope and by using the mathematical phantom corresponding approximately to the human body.

The Monte Carlo method is useful in the settlement of problems where interactions of photons with matters are governed by probabilistic rather than deterministic procedures.

Histories of photons that originate within the source organ are simulated by a computer in the Monte Carlo method. For any radioactive transformations, we know the energy of the emitted radiation, its starting point, and its initial direction. The probability of each interaction within the target organs and the energy transferred during each interaction are also known. Energy which is dissipated in a target organ by each interaction of photons is assumed to be absorbed in the target organ except for energy carried by photons scattered by compton scattering or photons produced by annihilation of a positron produced by pair-production. In this study, pair-production process is neglected since Tc-99m is a 0.14 Mev-monoenergetic photon emitter. Thus by dividing the energy absorbed by the target organ by the energy emitted by the source organ, absorbed fractions can be calculated.

With these absorbed fractions the internal radiation dose for the whole body can be obtained as follows ;

(i) The equivalent dose to a target T by radiation R, $H_{T,R}$, is

$$H_{T,R} = \omega_R \cdot D_{T,R} \qquad (1)$$

in which $D_{T,R}$ is the average absorbed dose of a target T by radiation R and ω_R is the radiation weighting factor.

(ii) The average absorbed dose, $D_{T,R}$, is given by

$$D_{T,R} = \frac{1}{M_T}\sum_i f_i \times E_i \times AF(T \leftarrow S)_i \qquad (2)$$

in which f_i is the fraction of transformations resulting in radiation of type i, E_i is the energy of radiation of type i emitted by the transformation of nuclide j in source organ S, $AF(T \leftarrow S)_i$ is absorbed fraction of the energy E_i, and M_T is the mass of target T.

(iii) The total equivalent dose, H_T, is represented by

$$H_T = \sum_R \omega_R \cdot D_{T,R} \qquad (3)$$

(iv) The effective dose, E, is given by

$$E = \sum_T \omega_T \cdot H_T \qquad (4)$$

in which ω_T is the tissue weighting factor of a target T.

(v) The committed effective dose, Ec, is given by

$$E_c = \int_0^{\infty} E(t)dt \qquad (5)$$

The value of ω_R is 1 for the photons, and the values of ω_T is shown in Table 3.

Table 3. Tissue weighting factor (ω_T)

ω_T	0.2	0.12	0.05	0.01
Organ, Tissue	Gonads	Colon Lung Red Marrow Stomach	Bladder Breast Liver Esophagus Thyroid Remainder	Bone Surface Skin

2.4 Development and Application of a Program -CAFRA-

CAFRA is a computer program which calculates the absorbed fraction of photons using the Monte Carlo technique. The program runs on an IBM-compatible personal computer in compiled FORTRAN.

The histories of 70,000 particles were simulated, and only compton scattering and photoelectric process were considered. The behavior of each particle is followed until the particle escapes from the phantom, its energy drops below a preset minimum, or the particle weight is less than 0.1. In any case, a new particle is sampled and its history is followed in the same way. The description of each subroutine is given in Table 4. The calculated results are shown Table 6.

3. Calculation of Effective Dose by Coordinate Transformation

For the purpose of analyzing the changes of committed effective dose due to the coordinate transformation, the coordinates of the organ was varied. Owing to its complexity, only the location changes of the source organ were tried without formal modification. In the coordinates of x-, y-, z-axis, the coordinate transformation of an organ can be generally expressed as follows;

[Source organ : Liver]

$$\left(\frac{x-x_0}{16.5}\right)^2+\left(\frac{y-y_0}{8}\right)^2\leq 1,\quad \frac{x-x_0}{35}+\frac{y-y_0}{45}-\frac{z-z_0}{43}\leq -1,\quad 27\leq z-z_0\leq 43$$

Boundary Condition : $-3.5 \leq x_0 \leq 3.5$, $-2 \leq y_0 \leq 2$, $-27 \leq z_0 \leq 27$

In this study, to determine (x_0, y_0, z_0), Latin Hypercube Sampling(LHS) was used since LHS can represent successfully the various probabilistic distribution with the small number of sampling. 10 cases have been chosen and analyzed. The coordinates of sampled (x_0, y_0, z_0) are shown in Table 5. The results are presented in Table 6.

Table 5. Coordinate Transformation by LHS

CASE	(x_0, y_0, z_0)	CASE	(x_0, y_0, z_0)
1	(-3.35, -0.41, 25.80)	6	(0.08, -0.91, 14.91)
2	(-2.25, 1.62, -16.68)	7	(0.78, 0.77, -7.78)
3	(-1.85, -0.05, -1.06)	8	(1.82, -1.29, 8.78)
4	(-0.72, 1.34, -14.26)	9	(2.66, 0.28, 0.78)
5	(-0.35, 0.85, -22.21)	10	(3.47, -1.99, 20.59)

4. Results and Conclusions

The results of calculation by CAFRA are given in Table 6, in which are tabulated the committed effective dose in case of dose assessment by Snyder model and dose changes by coordinate transformation, respectively. It shows that the results calculated by the program lie within 80%～100% of reference value. CAFRA can, therefore, be a simple tool to calculate absorbed fractions and effective dose when liver is chosen as a source organ. In the case of selecting other organs as a source organ, the program can be also applied with some modifications of input data and program. However, the bio-kinetic model was not considered in this study. By adding bio-kinetic model which can make it possible to evaluate the metabolism of radionuclides in the human body, the more sophisticated tool for internal dose assessment can be established.

Another calculation was performed to investigate the effects of coordinate transformation of a source organ on effective dose. With all the changes of coordinates for liver, the result in each case doesn't make a great difference. It means that the coordination changes of only the source organ don't have much influence on variation of committed effective dose. It, however, doesn't mean that the changes of organ location need not be considered in the calculation of internal dose. It is necessary to study the coordinate transformation of target organs as well as a source organ for the detailed evaluation of effective dose by coordinate changes.

It may be given as a conclusion that this study is of use as the basis for establishment of the Korean reference phantom that is suitable to Korean and in further study, the Snyder model may be used as an approximate phantom until the research on Korean reference man is adequately established..

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Table 2. Mathematical Description of Each Organ

Organ	Mathematical Description
Trunk	$\left(\frac{x}{20}\right)^2+\left(\frac{y}{10}\right)^2\le 1,\ 0\le z\le 70$
Liver	$\left(\frac{x}{16.5}\right)^2+\left(\frac{y}{8}\right)^2\le 1,\quad \frac{x}{35}+\frac{y}{45}-\frac{z}{43}\le -1,\quad 27\le z\le 43$
Stomach	$\left(\frac{x-8}{4}\right)^2+\left(\frac{y+4}{3}\right)^2+\left(\frac{z-35}{8}\right)^2\le 1,\ \left(\frac{x-8}{3.387}\right)^2+\left(\frac{y+4}{2.387}\right)^2+\left(\frac{z-35}{7.387}\right)^2\ge 1$
Small Intestine	$x^2+(y+3.8)^2\le 11.3^2,\quad -4.86\le y\le 2.2,\ 17\le z\le 27$
Upper Large Intestine	ascending colon : $(x+8.5)^2+(y+2.36)^2\le 2.5^2$, $(x+8.5)^2+(y+2.36)^2\ge 1.7915^2,\quad 14.45\le z\le 24$ transverse colon : $\left(\frac{y+2.36}{2.5}\right)^2+\left(\frac{z-25.5}{1.5}\right)^2\le 1,$ $\left(\frac{y+2.36}{1.793}\right)^2+\left(\frac{z-25.5}{0.973}\right)^2\ge 1,\ -10.5\le x\le 10.5$
Lower Large Intestine	descending colon : $\left(\frac{x-x_0}{1.88}\right)^2+\left(\frac{y-y_0}{2.13}\right)^2\le 1,\ \left(\frac{x-x_0}{1.58}\right)^2+\left(\frac{y-y_0}{1.34}\right)^2\ge 1,$ $8.72\le z\le 24,\quad \text{where } x_0=9+\frac{0.28(z-24)}{15.28},\ y_0=\frac{2.5(8.72-z)}{15.28}$ sigmoid colon : (upper portion) $[\sqrt{(x-3)^2+(z-8.72)^2}-5.72]^2+y^2\le 1.57^2,$ $[\sqrt{(x-3)^2+(z-8.72)^2}-5.72]^2+y^2\ge 0.91^2,\ x\ge 3,\ z\le 8.72$ (lower portion) $[\sqrt{(x-3)^2+z^2}-3]^2+y^2\le 1.57^2,$ $[\sqrt{(x-3)^2+z^2}-3]^2+y^2\ge 0.91^2,\quad x\le 3,\ z\ge 0$
Lung	left lung : $\left(\frac{x-8.5}{5}\right)^2+\left(\frac{y}{7.5}\right)^2+\left(\frac{z-43.5}{24}\right)^2\le 1,\quad z\ge 43.5,$ $\left(\frac{x-2.5}{5}\right)^2+\left(\frac{y}{7.5}\right)^2+\left(\frac{z-43.5}{24}\right)^2\ge 1 \text{ if } y<0$ right lung : $\left(\frac{x+8.5}{5}\right)^2+\left(\frac{y}{7.5}\right)^2+\left(\frac{z-43.5}{24}\right)^2\le 1,\ z\ge 43.5,$ $\left(\frac{x+2.5}{5}\right)^2+\left(\frac{y}{7.5}\right)^2+\left(\frac{z-43.5}{24}\right)^2\ge 1 \text{ if } y<0$
Thyroid	$x^2+(y+6)^2\le 2.2^2,\quad x^2+(y+6)^2\ge 1,\quad y+6\le 0,$ $70\le z\le 75,\quad [(y+6)-\lvert x\rvert]^2\ge 2[x^2+(y+6)^2]\tau^2,$ $\text{where } \tau=\frac{2(\sqrt{2}-2)}{5}(z-70)+1 \text{ for } 0\le z-70\le 5/4$ $\tau=\frac{2(2-\sqrt{2})}{15}(z-70)+\frac{2\sqrt{2}-1}{3} \text{ for } 5/4<z-70\le 5$
Testicle	right testicle : $\left(\frac{x+1.3}{1.3}\right)^2+\left(\frac{y+8}{1.5}\right)^2+\left(\frac{z+2.3}{2.3}\right)^2\le 1$ left testicle : $\left(\frac{x-1.3}{1.3}\right)^2+\left(\frac{y+8}{1.5}\right)^2+\left(\frac{z+2.3}{2.3}\right)^2\le 1$

Table 4. Description of Subroutines

Subroutine	Function
MAIN	▪ start and end of the calculation ▪ monitoring of the main sequence of the schematization
INPUT	▪ reading of the basic data and control parameters required by CAFRA
BEFOR	▪ preparatory calculatin in CAFRA ▪ construction of the cosine-sine table and the energy mesh table
BEHAV	▪ main control of particles
DEPAR	▪ selection of the initial source parameters
NECO	▪ determination of next collision point
EXTR	▪ exponential transformation
NEWA	▪ determination of the new wavelength after a compton scattering ▪ modification of the particle weight
ROPLA	▪ Russian Roulette play for the particle with a very low weight
DIREC	▪ selection of the photon's new direction after a compton scattering
CONT	▪ recording the particle's contribution to absorbed fraction
OUTPUT	▪ printing of results
SPLCO1	▪ performing the first stage of the cubic spline interpolation procedure
SPLCO2	▪ performing the second stage of the cubic spline interpolation procedure
GERANU	▪ generation of random numbers

Table 6. Comparison of Committed Effective Dose Case by Case

CASE	Committed Effective Dose (Sv/Bq)	Case/Snyder model	Case/ICRP-60
ICRP-60	3.70E-11	1.02	1.00
Snyder model	3.63E-11	1.00	0.98
Case 1	3.03E-11	0.83	0.82
Case 2	3.19E-11	0.88	0.86
Case 3	3.58E-11	0.99	0.97
Case 4	3.28E-11	0.90	0.89
Case 5	3.10E-11	0.85	0.84
Case 6	3.10E-11	0.85	0.84
Case 7	3.55E-11	0.98	0.96
Case 8	3.29E-11	0.91	0.89
Case 9	3.68E-11	1.01	0.99
Case 10	3.06E-11	0.84	0.83