InRaDoS: An internal radiation dosimetry computer program

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ABSTRACT

Introduction: Internal radiation dosimetry is important from a radiation protection point of view and can help to optimize the radiation dose delivered to the workers, public, and patients. It has a rather simple protocol but needs a large amount of data. Therefore, it is difficult to do on a routine basis. The use of computer programs makes internal radiation dosimetry simpler and less time consuming and also decreases the possibility of human errors.

Methods: The photon's specific absorbed fractions for two versions of Oak Ridge National Laboratory phantoms were calculated using MCNPX code and a Python code was used to calculate the S-values for selected radionuclides. Then calculated S-values transferred to an excel spreadsheet. The program's GUI was developed with the Tkinter module of Python programming language.

Results: A user-friendly program for internal radiation dosimetry was developed using Python programming language. This program allows the user to calculate the absorbed dose for 20 source organs in 23 target organs for two phantoms. Also, it is possible to compare the results of the two phantoms. Originally, 40 radionuclides were included in the program.

Conclusion: This program can be a useful tool for the assessment of organ absorbed doses for individuals dealing with radiation such as patients and workers. It decreases the time of dose calculation and helps to avoid human mistakes.

Key words: MIRD method; Specific absorbed fractions; S-values; Monte Carlo simulation; Absorbed dose

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INTRODUCTION

The use of radiopharmaceuticals in medicine for diagnostic and therapeutic purposes is increasing. The calculation of organ absorbed doses after the administration of radiopharmaceuticals to patients is one of the most important issues in nuclear medicine. This helps to optimize the administered activity to prevent deterministic effects and minimize the risk of stochastic effects on patients. The dose calculation from internally deposited radionuclides is not hard mathematically but needs a large amount of data [1]. It needs physical data such as the radionuclide's half-life and decay data. Also, the biological data such as the spatial distribution of radionuclide in the body is needed. It is hard to calculate the organ doses by hand on a routine basis and there is a possibility for human errors. Therefore, it is useful to have a computer program that includes radionuclide's physical and biological data to facilitate the dose calculations. Many program developed for internal radiation dosimetry such as MIRDOSE [2], OLINDA/EXM [3], and PCDOSE [1]. Also, an Iranian program developed which can calculate the total body, gonadal, and fetal dose for ^{99m}Tc [4]. In this study, a program was developed for the calculation of organ absorbed doses with the MIRD method.

METHODS

Programming language

For the development of InRaDoS (Stands for Internal Radiation Dosimetry Software), the Python programming language was selected. It is a general-purpose programming language that has a simple, easy to learn syntax and includes a rich set of modules in its standard library. Also, there are many third-party modules which readily available for it [5-7]. It is possible to run python on all hardware platforms and operating systems such as Linux, and Windows [7]. Most Python programs run unchanged on all major computer platforms [8]. The Python programming language is used for many applications such as website construction, numeric programming, game development, and so on [6-8].

Python includes a standard object-oriented interface to the Tk GUI called Tkinter (named Tkinter in Python 2.X), which has been a part of the Python standard library since 1994 with the release of Python version 1.1 [6, 8]. It supports a collection of Tk widgets (graphical components like buttons, text labels, and so on) that support most application needs [9]. It is easy to build a simple GUI application using Tkinter. The GUI is built by arranging and combining different widgets on the screen. Then, the users interact with widgets, causing events and your application responds to these events via functions you installed [7].

Phantoms

In this study, two versions of the OAK Ridge National Laboratory (ORNL) phantoms for an adult male was used. The first one belongs to a series of phantoms developed by Cristy et al. in 1987 [10], (hereafter referred to as ORNL/TM 8381 phantoms). The design of these phantoms described by Cristy [11] and is like the adult phantom of Snyder et al. [12], but several changes have been made in them. The tissue compositions and mass densities have been taken from ICRP publication 23 [13].

The second one belongs to the revised ORNL phantoms developed by Han et al. [14] and includes some revisions to the previous ORNL phantoms. These phantoms include head and brain models of MIRD pamphlet 15 [15], kidney's model of MIRD pamphlet 19 [16], prostate and rectum model published by Mardirossian et al. [17], extra thoracic/thoracic airways model published by Farfan et al. [18], salivary glands and the mucosa layer of most walled organs. The tissue compositions and mass densities have been taken from ICRP Publication 89 [19] and ICRU Report 46 [20].

Calculation method

The method developed by the Medical Internal Radiation Dose (MIRD) committee is commonly used for internal radiation dosimetry [21]. In this method, one can calculate the absorbed dose for a target organ, from one or more source organs which uniformly contain a radioactive source. The formula for calculation of absorbed dose in this method is as follows:

$$D = \tilde{A} \times S \qquad (1)$$

Where $\tilde{A}$ and S are cumulated activity and S-values respectively. The S-values calculated with the following formula:

$$S = \sum_i E_i n_i \Phi_i \qquad (2)$$

Where E_i and n_i are energy and intensity of ith decay of the radionuclide and the Φ_i is Specific Absorbed Fraction (SAF). The first two parameters are taken from decay data tables but the SAFs commonly are calculated using the Monte Carlo method for the interactions and fate of photons (or other radiations) following their emission from the source organ [22].

The cumulated activity is the total number of nuclear disintegrations in the source organ and defined as follows:

$$\tilde{A} = \int_0^\infty A(t)dt \qquad (3)$$

Where A(t) is a function that describes the variation of activity with time in the source organ. The time-activity curves can be very complex, and thus the calculation of equation (3) can be difficult. However, for the simplification of calculation, some assumptions can be made. If the uptake by the organ is very rapid with respect to the half-life of radionuclide and there is no biologic excretion [23], the only mechanism that removes the radioactivity from the source organ is radioactive decay and then cumulated activity calculated as follows:

$$\tilde{A} = \int_0^\infty A(t)dt = \int_0^\infty A_0 e^{-0.693t/T_{1/2}} dt = \frac{A_0 T_{1/2}}{0.693} \qquad (4)$$

Where $T_{1/2}$ is the physical half-life of the radionuclide, and A_0 is the initial activity of the source organ. In this program, equation (4) is used for the calculation of cumulated activity. Thus, the program needs two datasets: one for S-values and one for half-lives. The decay data and half-lives of the radionuclides were taken from data provided by the RADAR site [24]. The S-values were calculated with the formula (2). The decay data in this formula (E_i and n_i) were taken from data provided by the RADAR site [24] and the SAFs were calculated using the Monte Carlo method.

Monte Carlo simulation

As described earlier, The Monte Carlo method is commonly used for the calculation of SAF values. In this study, MCNPX code version 2.6.0 that developed by the Los Alamos National Laboratory (LANL) was used. MCNP is a general-purpose Monte Carlo code that can simulate the transport of many types of particles in three-dimensional geometries over broad ranges of energy [25].

MCNP's rejection technique was used to define the source organ [26]. In this method, one needs to define a volume that encompasses the source organ. It is not possible to define a very large volume because if the sampling efficiency in the source cell is too low, the simulation ends with a fatal error. Therefore, the trial and error method can be used to define the optimum volume.

The photon's SAF values for ORNL/TM 8381 and revised ORNL phantom were calculated using MCNPX code for 12 energies between 0.01 to 4 MeV. The SAFs were calculated for 20 source organs in 23 target organs (Table 1). All the results have a coefficient of variation ($100 \, ^{\sigma_\Phi}/_\Phi$) less than 10%. Then, the results were transferred to an excel spreadsheet. The photons with energies below 0.01 MeV, were considered as non-penetrating radiation.

For beta radiations, the SAF was taken as zero if the source and target organs are different and as $\frac{1}{m_k}$ if the

source and target organs are the same where m_k is the mass of the target organ. For organs with walls and contents such as the stomach and when the contents is the source, the value of SAF was taken as $\frac{1}{2m_h}$ where m_h is the mass of the source organ [27].

Table 1: Available source and target organs in the program.

Organ	Use as source organ	Use as Target organ
Adrenals	Yes	Yes
Brain	Yes	Yes
Breasts	Yes	Yes
GB[a] contents	Yes	No
GB wall	No	Yes
LLI[b] contents	Yes	No
LLI wall	No	Yes
SI[c]	Yes	Yes
Stomach contents	Yes	No
Stomach wall	No	Yes
ULI[d] contents	Yes	No
ULI Wall	No	Yes
Heart contents	Yes	No
Heart Wall	No	Yes
Kidneys	Yes	Yes
Liver	Yes	Yes
Lungs	Yes	Yes
Muscle	No	Yes
Ovaries	Yes	Yes
Pancreas	Yes	Yes
Skin	No	Yes
Spleen	Yes	Yes
Testes	Yes	Yes
Thymus	Yes	Yes
Thyroid	Yes	Yes
UB[e] contents	Yes	No
UB wall	No	Yes
Uterus	Yes	Yes
Total Body	No	Yes

a:Gallbladder, b:Lower Large Intestine, c=Small Intestine, d:Upper Large Intestine, UB=Urinary Bladder

Calculation S-values

A Python code was written to calculate S-values for different radionuclides. This code uses the excel spreadsheet of SAF values and energy and intensities of gamma and beta radiations of radionuclides for calculation of S-values. Since many of the gamma energies of radionuclides are between 12 simulated energies, the 1-D interpolation was used to calculate SAF values for them.

For validation purposes, the Photon's SAF values for ORNL/TM 8381 phantom were downloaded from the RADAR site [24]. Then calculated S-values for [18]F

with Python code (for 20 source organs and 23 target organs and therefore 460 S-values) were compared with data provided by Stabin et al. [28]. For 455 S-values (almost 99% of cases), the Relative Difference (RD) is below 1%. In four cases, the RD is >1% and <2%, and only in one case, the RD is almost 5%.

Table 2 compares the S-values calculated using Python code with S-values provided by Stabin et al.

[28] for adrenals and lungs. Therefore there is very good agreement between the results of python code and the data provided by Stabin et al. [28]. The calculated S-values were saved in a separate excel spreadsheet, and the program uses these data for dose calculations. For now, 40 radionuclides are included in the program (Table 3).

Table 2: [18]F S-values calculated using Python code and S-values provided by Stabin et al. [28] for adrenals and lungs.

Target Organ	Adrenals			Lungs		
	Python code	**Stabin et al.**	**RD %**	**Python code**	**Stabin et al.**	**RD %**
Adrenals	2.63E-03	2.59E-03	1.54	1.74E-06	1.74E-06	0.00
Brain	1.12E-08	1.12E-08	0.00	9.69E-08	9.70E-08	-0.10
Breasts	4.59E-07	4.60E-07	-0.22	1.74E-06	1.74E-06	0.00
GB[a] Wall	2.21E-06	2.21E-06	0.00	5.53E-07	5.54E-07	-0.18
LLI[b] Wall	2.06E-07	2.06E-07	0.00	4.93E-08	4.93E-08	0.00
SI[c]	5.70E-07	5.70E-07	0.00	1.40E-07	1.40E-07	0.00
Stomach Wall	1.74E-06	1.74E-06	0.00	8.22E-07	8.23E-07	-0.12
ULI[d] Wall	6.81E-07	6.81E-07	0.00	1.74E-07	1.75E-07	-0.57
Heart Wall	2.05E-06	2.05E-06	0.00	3.00E-06	3.00E-06	0.00
Kidneys	5.21E-06	5.22E-06	-0.19	5.07E-07	5.08E-07	-0.20
Liver	3.00E-06	3.01E-06	-0.33	1.37E-06	1.38E-06	0.72
Lungs	1.74E-06	1.74E-06	0.00	4.69E-05	4.69E-05	0.00
Muscle	8.53E-07	8.54E-07	-0.12	6.80E-07	6.80E-07	0.00
Ovaries	2.69E-07	2.69E-07	0.00	7.61E-08	7.62E-08	-0.13
Pancreas	7.10E-06	7.11E-06	-0.14	1.23E-06	1.23E-06	0.00
Skin	3.16E-07	3.17E-07	-0.32	3.48E-07	3.48E-07	0.00
Spleen	3.16E-06	3.16E-06	0.00	1.14E-06	1.14E-06	0.00
Testes	3.18E-08	3.19E-08	-0.31	1.02E-08	1.03E-08	-0.97
Thymus	4.90E-07	4.90E-07	0.00	2.05E-06	2.06E-06	-0.49
Thyroid	8.90E-08	8.92E-08	-0.22	6.64E-07	6.65E-07	-0.15
UB[e] Wall	1.03E-07	1.03E-07	0.00	2.71E-08	2.71E-08	0.00
Uterus	2.21E-07	2.21E-07	0.00	5.87E-08	5.88E-08	-0.17
Total Body	1.49E-06	1.49E-06	0.00	1.30E-06	1.30E-06	0.00

a:Gallbladder, b:Lower Large Intestine, c=Small Intestine, d:Upper Large Intestine, UB=Urinary Bladder
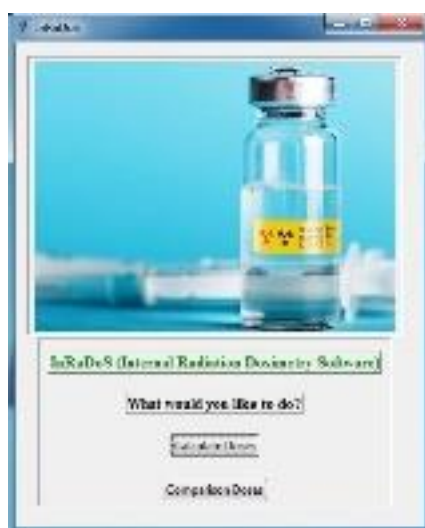
Table 3: Radionuclides that included in the program.

Radionuclides									
^{3}H	^{7}Be	^{11}C	^{13}N	^{14}C	^{15}O	^{18}F	^{22}Na	^{24}Na	^{28}Mg
^{28}Al	^{32}P	^{35}S	^{37}Ar	^{40}K	^{42}K	^{43}K	^{45}Ca	^{47}Ca	^{47}Sc
^{49}Sc	^{51}Cr	^{52}Mn	^{52m}Mn	^{52}Fe	^{54}Mn	^{59}Fe	^{62}Cu	^{67}Ga	^{68}Ga
^{75}Se	^{82}Rb	^{87m}Sr	^{99m}Tc	^{111}In	^{113m}In	^{123}I	^{125}I	^{131}I	^{201}Tl

RESULTS AND DISCUSSION

InRaDoS is a program that allows calculating the organ absorbed doses for two versions of ORNL phantoms. For now, 40 radionuclides are included in the program, and calculation can be done for 20 source organs in 23 target organs. The program uses the radionuclide's S-values and half-life to calculate the organ absorbed doses in mGy.

The program has a user-friendly GUI that helps the users to simply calculate the organ absorbed doses. The main window of the program has two buttons as shown in Figure 1: "Calculate Doses" and "Compare Doses".

Fig 1. The main window of the program.

output (Figure 3). To return to the main menu, users can click on the "Back to Main Menu" button.

Fig 2. The window for dose calculation.

Fig 3. The window for results of dose calculation.

Calculate doses: By clicking this button, a new window appears (Figure 2). The user chooses the phantom type, radionuclide, and the source organ and then enters the initial activity in the source organ in MBq. The program uses these data to calculate the organ absorbed dose in all target organs. The user can see the results by clicking on the "Show results" button or save the results as a PDF file by clicking on the "Save Results" button. All of the input parameters (phantom type, radionuclide, …) are shown in the

Compare doses: By clicking this button, a new window appears (Figure 4). The user chooses the radionuclide and source organ and then enters the initial activity in the source organ in MBq. The program uses these data to calculate organ absorbed doses for both phantoms and also compares the results and calculates the difference of them in % (The data of ORNL/TM 8381 used as reference data). The users can see the results by clicking on the "Show Results" button (Figure 5) or save the results as a PDF file by clicking on the "Save Results" button.
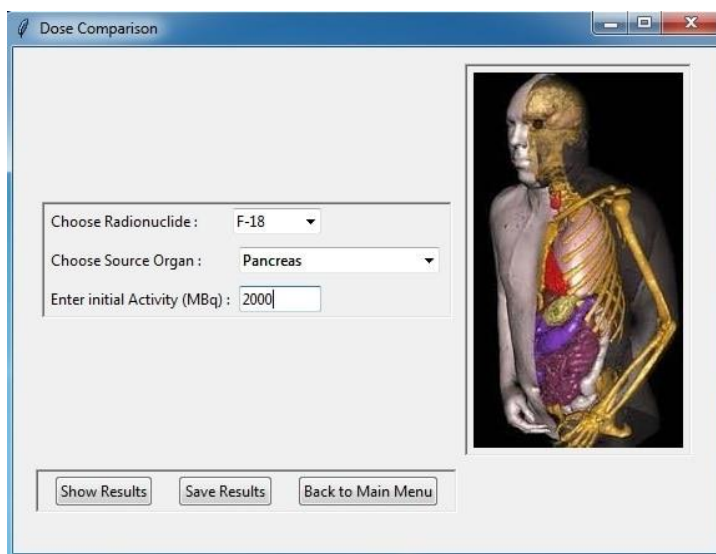
Fig 4. The window for comparison of the results of the two phantoms.

Fig 5. The window for results of dose comparison.

To return to the main menu, users can click on the "Back to Main Menu" button.

Since this is the first version of the program, it has some problems that should be solved in the next versions. First of all, as stated in the calculation method, the program calculates the cumulated activity with a simple assumption (fast uptake by the organ with no biologic excretion). Therefore, the biological distribution of radionuclides in the body is not considered in the program. Also, in each calculation, the user can choose only one source organ. Finally, the phantoms that were used in this study are mathematical phantoms. Nowadays, the use of voxel phantoms in internal dosimetry is increasing because they simulate the human body more accurately than stylized phantoms. Therefore, it is intended to add a voxel phantom data to the program in the future.

Despite these problems, this program can be a useful tool for the automatic calculation of organ absorbed doses. It can be used to assess the internal radiation dose to patients in nuclear medicine and the radiation dose to workers in nuclear facilities. Also, it can be used for educational or regulatory purposes.

CONCLUSION

In this work, a computer program was developed using Python programming language which can be used for internal radiation dosimetry. The program uses MIRD methodology for the calculation of organ absorbed doses for two different phantoms. The program has a user-friendly GUI that facilitates internal radiation dosimetry and can help to save time and avoid human mistakes in dose calculations. The user chooses the phantom type, radionuclide, source organ, and enters initial activity in the source organ in MBq. The program uses these data and s-values and half-life of selected radionuclide to calculate the organ absorbed doses in mGy. Since it is the first version of the program, it has some problems that should be solved in the next versions. However, it is a useful tool for internal radiation dosimetry and can be used in many fields dealing with radiation. For future developments,

it is intended to increase the number of available radionuclides and also add a voxel phantom to the program.

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