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RadNuc: A graphical user interface to deliver dose rate patterns encountered in nuclear medicine with a ¹³⁷Cs irradiator

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Abstract

The temporal variations in absorbed dose rates to organs and tissues in the body are very large in diagnostic and therapeutic nuclear medicine. The response of biological endpoints of relevance to radiation safety and therapeutic efficacy are generally modulated by dose rate. Therefore, it is important to understand how the complex dose rate patterns encountered in nuclear medicine impact relevant biological responses. Accordingly, a graphical user interface (GUI) was created to control a cesium-137 irradiator to deliver such dose rate patterns.

Methods—Visual Basic 6.0 was used to create a user-friendly GUI to control the dose rate by varying the thickness of a mercury attenuator. The GUI facilitates the delivery of a number of dose rate patterns including constant, exponential increase or decrease, and multi-component exponential. Extensive visual feedback is provided by the GUI during both the planning and delivery stages.

Results—The GUI controlled irradiator can achieve a maximum dose rate of 40 cGy/hr and a minimum dose rate of 0.01 cGy/hr. Addition of machined lead blocks can be used to further reduce the minimum dose rate to 0.0001 cGy/hr. Measured dose rate patterns differed from programmed dose rate patterns in total dose by 3.2% to 8.4%.

Conclusion—The GUI controlled irradiator is able to accurately create dose rate patterns encountered in nuclear medicine and other related fields. This makes it an invaluable tool for studying the effects of chronic constant and variable low dose rates on biological tissues in the contexts of both radiation protection and clinical administration of internal radionuclides.

Keywords

variable dose rate irradiator; chronic low dose rate irradiation; mercury attenuator; cesium-137; software development

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Introduction

According to a recent report issued by the National Council on Radiation Protection and Measurements (NCRP), the general public in the United States is being exposed to increasing levels of ionizing radiation [1]. This increase is largely due to the multitude of medical imaging procedures and technological advancements that have developed over the last two decades, particularly computed tomography (CT) and nuclear medicine. In fact, the contribution of nuclear medicine procedures to the estimated annual average radiation exposure to the general public has increased almost 600% from the 1992 estimates [2]. This has occurred as a consequence of the indispensable role that radiopharmaceuticals play in diagnostic medicine. While therapeutic nuclear medicine procedures were not included in the NCRP estimates of annual exposures, radiopharmaceuticals also play important roles in pain management and in the treatment of cancer.

The ionizing radiations emitted by radiopharmaceuticals deliver radiation absorbed doses to various organs and tissues over protracted times that depend on the biological uptake and clearance half-times of the radiopharmaceutical in the tissue and the physical half-life of the radionuclide. The corresponding dose rate patterns that emerge are continuously variable and uniquely different than most encountered in other diagnostic and therapeutic modalities that usually involve either single or multiple fractionated acute exposures. There is a wealth of knowledge that has been gained regarding the biological effects of single or multiple fractionated acute exposure patterns as well as the effects caused by chronic irradiation at constant dose rate [3]. Research has shown that responses to continuous radiation exposures are markedly different from responses to an acute exposure [4]. Depending on the tissue irradiated, the underlying reasons behind these differences have been attributed to a multitude of factors such as cell cycle dependence of radiosensitivity, proliferation, cell signaling, inflammatory responses, adaptive responses, compensatory responses, and many other factors such as linear energy transfer (LET). The relative importance of such factors depends on the dose rate and total absorbed dose. Yet, there is a paucity of data available regarding how the exponentially varying dose rates encountered in nuclear medicine affect response, especially under conditions that are not influenced by the spatial nonuniformities of dose that are often inherent in nuclear medicine. This is relevant not only for diagnostic nuclear medicine, but also for radioimmunotherapy (RIT) utilized in the treatment of cancers [5]. The main drawback of RIT is the exposure of non-targeted tissue to chronic radiation exposures. RIT collateral damage is a significant concern and alternative procedures like pretargeted RIT have been developed in an effort to reduce it. Hematologic toxicities are typically the most problematic with respect to RIT [6], however kidney toxicity is prevalent for radiolabeled peptides. More data concerning biologic responses to the dose rate patterns associated with these modalities could lend insight into the effectiveness and toxicity of new and existing procedures. Furthermore, research on responses to low dose rate would also advance the field of radiation protection, as there is debate about the measures that must be taken to ensure the safety of people exposed to chronic low dose rate exposures. Some contend that the risks of low dose rate radiation have been overestimated, and that this is detrimental to both the mental and physical health of the public [7]. In a similar fashion, some studies have shown that there exists a threshold for the biological effects of low dose rate irradiation [8]. There are also proponents of the linear no-threshold model, asserting that it is a valid basis for radiation risk estimation [9]. Taken together, it is apparent that more chronic low dose rate data is necessary in order to reach a consensus on these crucial and relevant issues.

To conduct radiobiology studies relevant to nuclear medicine, a ^{137}Cs low dose rate irradiator was previously constructed to deliver radiation dose rate patterns that simulate those encountered upon administration of internal radionuclides [10]. However, the original

software had a non-intuitive text-based user interface and offered only limited dose rate patterns. Accordingly, we set out to create a multifunctional and user-friendly irradiator capable of delivering chronic exposures with variable dose-rates. This required replacing key hardware, developing entirely new programs to operate the hardware components of the irradiator, and most importantly, creating a graphical user interface (GUI) to facilitate the *planning* and delivery of a wide array of temporal patterns of radiation dose rate. This irradiator was designed to overcome some of the limitations of other custom low dose rate irradiators. For example, Olipitz et al. designed an irradiator which is capable of producing different low dose rates of 28–30 keV x- and γ -rays depending upon the amount of ^{125}I placed into it [11]. Another ^{125}I irradiator is capable of producing either continuous or acute low dose rate exposures [12]. Our irradiator/interface system, which uses only a single sealed ^{137}Cs source, was designed to provide continuous irradiation patterns that are present following administration of diagnostic and therapeutic radionuclides. Data collected from the use of this irradiator enables scientists to gain information about the biological effects of continuous low dose rate irradiation that many medical procedures entail. Such information is difficult to garner from epidemiological studies where it is difficult to control the myriad variables [13]. The high degree of environmental control afforded by this irradiator facilitates the removal of confounding variables. This further expands the utility of our device, and makes it an effective tool for the study of chronic low dose rate effects.

Materials and Methods

Irradiator

The irradiator consisted of a $121.92 \times 22.86 \times 33.02$ cm lead cabinet with a downward facing 666 GBq ^{137}Cs source located on top [10]. This was coupled to a mercury attenuator system that consisted of two chambers of mercury, one inside the irradiator and one outside (Figure 1). The chambers of mercury were connected by two tubes: a siphon tube to transfer mercury between the chambers and an air line to maintain neutral pressure during transfer. This attenuator system controlled the thickness of mercury present in the fixed-position internal box (Hg attenuator) by manipulating the height of the external box (Hg reservoir). Temporal variation of the thickness of mercury in the internal box resulted in temporally varying dose rates within the irradiator. Gamma ray attenuation is an exponential function of mercury thickness, so a linear change in mercury thickness resulted in an exponential change in dose rate. Movement of the external mercury box was provided by a motion control system consisting of a Daedal (Harrison City, PA) Model 106061C cross-roller table fitted with a Model 04M lead screw (0.4 mm/revolution), Parker 006-1375-02 optical LHO, Model 4990-06 z-axis brackets, and Compumotor (Rohnert Park, CA) Model 567-102-MO stepper motor. The stepper motor was controlled with a Compumotor Zeta series drive (Model 83-135) and Compumotor ACR 9000 two-axis indexer equipped to handle exponential functions within a Microsoft XP environment.

The irradiator is housed in an environmental chamber with humidity and temperature controls. Lucite sample boxes are available with fittings to accommodate gas lines that are routed into the environmental chamber from a storage closet outside the chamber. Accordingly, samples can be maintained in desired gas conditions by providing premixed gases (e.g. 5% CO_2 – 95% air).

Graphical User Interface and Irradiator Control

Overview—Visual Basic 6.0 was used to create a computer program to control the irradiator with a user-friendly GUI. A tabbed interface was developed to enable users to plan and execute delivery of a variety of radiation dose rate patterns. Each tab corresponds to a different dose rate pattern, and features unique characteristics related to its specific pattern.

Three dose rate patterns are available including constant (Figure 2), exponential increase/decrease (Figure 3A–B), and multi-component exponential (Figure 3C). The date is displayed on each tab, because the program accounts for gradual reduction of the ^{137}Cs source strength due to its decay with a 30 year physical half-life. The GUI was designed so that it can be utilized intuitively by someone without programming knowledge and who is unfamiliar with the details of the irradiator. Upon execution of the program, the user must click the “Connection/Properties” tab and then click the “Connect” button which opens a channel of communication between the computer and the indexer and enables the drive that funnels commands from the indexer to the motor. It also commands the motor to go to the home position, which corresponds to minimum mercury thickness in the Hg reservoir. Each of the dose rate pattern tabs feature input that centers upon three parameters: total dose, initial dose rate, and irradiation time. The program uses cGy as the unit for radiation absorbed dose and hours as the unit for time. The user is asked to provide any two of these three parameters. A calibration curve is also present on each tab to aid users in planning their experiments. The calibration curve provides the range of dose rates that can be delivered at different positions within the irradiator, made possible by mercury movement. The configuration of the irradiator refers to the presence or absence of lead blocks placed against the bottom of the internal mercury box. The irradiator is equipped with several precision-machined lead blocks (JL Shepherd) that can be combined to decrease the dose rate ranges in the irradiator by a factor of 2, 4, 10, 20, 25, 50, or 100. Each tab features a “Lead Block” drop down box with these numbers, so that the user can select one if he/she desires a lower dose rate. Upon selecting a lead block combination, the calibration curve shifts downward to reflect the dose rate ranges of the new attenuator configuration. Without any lead blocks, the maximum dose rate possible in the irradiator on 1/12/2012 was 40.2 cGy/hr and the minimum dose rate possible was 0.011 cGy/hr. With the addition of lead blocks, the minimum dose rate attainable in the irradiator was extended to 0.00011 cGy/hr. Table 1 displays the attainable dose rates at different positions within the irradiator.

Constant dose rate tab—The GUI for planning and delivering constant dose rates requires the entry of values for two of the parameters total dose, dose rate, and time. Upon their entry, the user clicks NEXT the software calculates the third parameter and determines the distance from the source where the sample must be placed. This algorithm starts at the bottom of the irradiator, 1194 mm from the source. It determines whether the desired dose rate can be achieved at this position by changing the thickness of the mercury attenuator. If it can, then 1194 mm is selected as the sample position. If it cannot, then 1193 mm is tested. The algorithm continues in this fashion until it reaches the minimum possible distance from the source, 126 mm. If the dose rate desired cannot be achieved at this position, an error message is generated that informs the user about the maximum and minimum dose rates that can be delivered by the irradiator configuration that was selected. The algorithm starts at the bottom of the irradiator because errors in sample position have the least impact on the dose rate when the sample is the farthest possible distance from the source. A precision tape measure is affixed to the inside of the irradiator along its entire height such that the mm hash marks correspond to the sample positions that the program dictates to the user via a message box. The program also activates the stepper motor at this time to adjust the mercury thickness in the internal box so that the proper initial dose rate can be achieved. Upon completion of the initial move, the user is advised to wait ten minutes to allow the mercury thickness to equilibrate. This relatively lengthy time is requested because a very large change in mercury thickness may be required to achieve the specified initial dose rate. Graphs of dose rate versus time, dose versus time, and millimeters of mercury versus time are displayed within the GUI. Analogous to treatment planning in radiation oncology, these graphs give the user visual feedback for planning an experiment. The user can also click on specific points on each graph and a window will pop up informing them of the abscissa and

ordinate values of that point. Changes to the plan are achieved by clicking the STOP button. If the user accepts the plan, the user places the sample at the location within the irradiator specified by the program. After allowing the mercury to equilibrate, the user manually activates the lever that extracts the ^{137}Cs source from its shield and clicks the OK button on the message box to commence the experiment. Upon clicking OK, a timer built into the software is activated. The dose, dose rate, and mercury thickness graphs are updated every ten minutes with purple stars so that the user will know the progress of the experiment at all times. Ten minutes is the default time interval, but this can be changed by the user to any desired interval. The millimeters of mercury versus time graph allows the user to verify that the thickness of mercury in the attenuator box corresponds to the planned thickness at a given time. This verification is facilitated by a ruler attached to the external mercury box that is positioned so that its mercury level on the ruler corresponds to the amount of mercury in the internal attenuator box. When the experiment is completed, a message box informs the user and requests that the source be manually retracted into its shield.

Exponential increase/decrease dose rate tab—This tab, shown in Figure 3A–B, functions in a similar fashion to the constant dose rate tab. The user must enter two of the following three parameters: dose, initial dose rate, and time. Additionally, the user must select whether they want an exponentially increasing (Figure 3A) or decreasing (Figure 3B) dose-rate pattern and then enter a corresponding half-time T_d . Next to the increasing and decreasing options are their respective functions:

$$r(t) = r_o e^{0.693t/T_d} \quad (1)$$

$$r(t) = r_o e^{-0.693t/T_d} \quad (2)$$

where r is the dose rate at time t , and r_o is the initial dose rate at $t = 0$. The program calculates the remaining parameters and then determines the maximum and minimum dose rates for the plan. It then attempts to find a position within the irradiator at which both the maximum and minimum dose rates can be achieved within the constraints of the mercury attenuator. The algorithm starts at the bottom of the irradiator and works its way up. The program can fail to find a position for one of two reasons. The first, which was discussed above, is that one of the dose rates cannot be achieved in the selected irradiator configuration. The second, however, relates to the dose-rate range desired by the user. Because the maximum change in mercury thickness is 35.8 mm, a given position in the irradiator can only experience a 125 fold range of dose rates resulting from changes in mercury thickness (the measured attenuation coefficient is 0.135 cm^{-1}). An experiment in which there is a difference in dose rate ranges greater than a factor of 125 prompts a message box informing the user of the maximum and minimum dose rates that are required for their desired experiment, the fold change in dose rate that is required, and that their plan exceeds the limit of a 125 fold change. This feedback enables the user to adjust the parameters to deliver a range of dose rates within the capability of the irradiator. Once a sample position for the plan is found, the plan is graphed (red lines) and the user starts the irradiation procedure as described above. The software moves the stepper motor every five minutes to adjust the mercury thickness so that the desired dose rate pattern is delivered, and updates the graphs with purple datum points every ten minutes (or at some other interval set by the user). Figures 3A and 3B also depict examples of the exponential increase/decrease tab at two different stages of completion during different example experiments. The dose rate versus time graph can be displayed with either a linear axis or a semi-logarithmic axis on this tab. The semi-log axis enables the user to verify that the pattern created is exponential in nature. The user is able to flip between linear and semi-log axes at will at any

time throughout the experiment. When the planned irradiation is completed, the program informs the user and requests that the source be manually retracted into its shield.

Multi-component exponential dose rate tab—The multi-component exponential tab provides capability to simulate irradiation conditions that occur during biexponential clearance patterns that are often observed for radiopharmaceuticals in organs and tissues. Simulation of irradiation conditions during exponential uptake followed by exponential clearance is also facilitated by this tab. The user inputs two of the following three parameters: dose, extrapolated initial dose rate (r_o'), and time. The extrapolated initial dose rate corresponds to the point on the dose-rate axis when the clearance curve is extrapolated back to $t=0$ [14, 15]. As per Equation 3 which is also displayed on the tab, the user must also enter values for a, b, and corresponding increase (T_i) and decrease (T_{d1} , T_{d2}) half times.

$$r(t) = r_o' \left(a e^{-0.693t/T_{d1}} + (1 - a) e^{-0.693t/T_{d2}} - b e^{-0.693t/T_i} \right) \quad (3)$$

The parameter a controls the relative importance of the exponentially decreasing components (there can be either one or two components), and the parameter b controls whether or not there is an exponentially increasing component. After entering values of a and b ($0 \leq a \leq 1$, $0 \leq b \leq 1$), the user must then enter the corresponding half-times. Upon receiving the tab's required data, the program calculates the remaining parameters and determines the minimum and maximum dose rates for the planned irradiation. Starting at the bottom of the irradiator, it attempts to find a position that can achieve these dose rates. Again, there are two reasons that a position may not be found, and both situations are dealt with in the manner described above. Once a position is found, the user is notified and the plan is graphed with a red line. The plan is then implemented as described above for other patterns. Figure 3C depicts the multi-component exponential tab upon completion of delivery of a planned irradiation protocol.

GUI Error Messages—The GUI is designed to provide the user with a variety of messages to guide the planning of an irradiation protocol. Table 2 enumerates the error messages along with their cause, and a brief description of how to resolve the error.

Calibration of GUI Controlled Irradiator

To calibrate the GUI controlled irradiator, an ionization chamber was used to continuously measure the dose rate at various locations within the irradiator during delivery of the planned irradiation protocol. A Radcal (Monrovia, CA) Radiation Monitor Controller 9010 was utilized, equipped with a 90×6 60 cc ionization chamber. The chamber was calibrated by Radcal and was tested for conformance with Radcal specifications using applicable ISO 9001:2008 conformance test procedures. Readings were automatically corrected for the measured temperature of 32°C and measured pressure of 99.0 kPa.

Results

The GUI controlled low dose rate irradiator was tested using a number of different dose rate patterns. First, an exponentially increasing dose rate pattern was tested by selecting Exponentially Increasing Dose Rate in the Exponential Dose Rate Pattern tab and entering the following: $D = 26.797$ cGy, $T_d = 1.83$ hr, and $t = 12$ hr. The initial dose rate was automatically calculated to be $r_0 = 0.109$ cGy/hr. Ionization chamber measurements of the dose rate and cumulative absorbed dose showed that the GUI controlled irradiator actually delivered a dose rate pattern very similar to the planned irradiation with a –8.0% difference in the absorbed dose delivered over the 12 hr period (Figure 4A). Another programmed dose

rate pattern was intended to simulate the dose rate pattern that could be delivered to an organ or tissue following uptake of ^{18}F , a very common diagnostic radionuclide often used in positron emission tomography [16, 17]. This radionuclide has a physical half-life of 1.83 h and a spectrum of biological clearance half-times are possible depending the radiopharmaceutical, organ, etc. Accordingly, a simple experiment was conducted to deliver the same dose as above by selecting Exponentially Decreasing Dose Rate tab and entering the following: $r_0 = 10$ cGy/hr, $T_d = 1.83$ hr, and $t = 12$ hr. The dose was automatically calculated to be $D = 26.797$ cGy. The measured pattern resembled the programmed one, with a 3.2% error in the delivered dose (Figure 4B).

In addition, an exponentially decreasing dose rate pattern meant to simulate the decay of ^{123}I , a radionuclide used in both diagnostic and therapeutic nuclear medicine, was run. The ^{123}I dose rate pattern was assigned an $r_0 = 40$ cGy/hr, $T_d = 13.22$ hr, $t = 73$ hr, and a dose of 744.886 cGy was automatically calculated (Figure 3B). The dose rate pattern produced by the GUI controlled irradiator was highly representative of the programmed pattern, with a 4.6% error in the delivered dose (Figure 4C).

Finally, a multi-component exponential dose rate pattern was selected in the corresponding GUI tab. It consisted of an increasing component and a single decreasing component, intended to simulate the uptake and subsequent decay of an internally-administered radionuclide. The dose rate pattern was assigned the parameters $r_0 = 0.06$ cGy/hr, $a = 1$, $b = 0.99$, $T_i = 4$ hr, $T_{d1} = 8$ hr, $T_{d2} = 1$ hr, $t = 24$ hr, and the dose was automatically calculated to be 26.797 cGy (Figure 3C). The measured pattern resembled the intended one, albeit with a somewhat higher -8.4% error in the delivered dose (Figure 4D). Interestingly, this error is about the same as that obtained for Figure 4A despite an apparently greater difference. However, integration of the areas under the measured and predicted curves using the Sigmaplot V12.3 (Systat Software Inc.) area tool confirms the errors.

Discussion

The data presented in Figure 4 demonstrate that the GUI controlled irradiator can generate meaningful and clinically relevant dose rate patterns. The errors encountered in the total dose delivered ranged from -8.4 to +4.6% depending on the dose rate profile tested. These are within reasonable bounds considering the complexity of the dose rate patterns, and suggest that our calibration and attenuation coefficients are within acceptable bounds. These errors in dose delivery likely arise as a result of the time required for the mercury thickness in the attenuator chamber to equilibrate following each move of the mercury reservoir (Figure 1). The software moves the reservoir step-wise every five minutes, which results in dozens of moves over the course of experiments when dose rate increase and decrease half-times are in the range of hours. Depending on the dose rate profile, each move will differ in magnitude and the time required for the mercury to equilibrate will change accordingly. The time it takes for the mercury to equilibrate after these moves can lead to error in the actual dose rate delivered at a given time t because the actual mercury thickness would be a little “behind” where it was programmed to be at that time t . Additionally, the errors in positioning of the ionization chamber probe may also be responsible for some of the error observed. As described above, the program tells the user where within the irradiator to place the sample. Because the dose rate decreases with the square of distance from the source, the error in delivered dose due to improper positioning of the sample can be significant, particularly when the source to sample distance is short. Nevertheless, the serial ionization chamber measurements conducted in these studies suggest that the resulting errors are below 10%.

The GUI controlled irradiator described here can be used to acquire radiobiological data on the consequences of low dose rates of low-LET ionizing radiation delivered at constant and variable dose rates. There is a paucity of such data, and as such there are a number of issues that it could help to clarify. For example, exposure to low doses of ionizing radiation has increasingly become a matter of scientific and public concern and debate. Public exposure to ionizing radiation is due mainly to chronic irradiation by “ubiquitous background” radiation [2]. The GUI controlled irradiator can simulate the constant dose rate patterns delivered by low-LET background radiations, as well as those encountered in the work environments of airline pilots, astronauts, and x-ray technicians. In addition, our GUI controlled irradiator can be utilized to study the radiobiology of numerous medical procedures that involve the administration of radionuclides into the body. The multi-component exponential dose rate pattern is able to simulate the dose rate patterns that a tumor could receive in a variety of targeted therapies. The dose rates that can be delivered by the irradiator are suitable for simulating those encountered in radioimmunotherapy which reach values up to about 40 cGy/hr [18, 19]. Total doses delivered to the red marrow and kidneys are typically below 100 cGy [20–22], which can be easily replicated in the irradiator. It has also been shown that low dose rates (below 10 cGy/hr) may cause tumor cells to pile up in the radiosensitive G2 phase, allowing for a higher kill success when chased with a large acute dose [23]. Tumor cells have been observed to exhibit an inverse dose rate-to-kill relationship in some cases as well, suggesting that in some instances lower dose rates may be better suited to therapy than higher ones [24]. Finally, the dose rate patterns that can be delivered by this irradiator can also serve as a useful control radiation when determining the relative biological effectiveness of alpha particle emitters and Auger electron emitters [25]. These are just a few examples of findings that can be expanded upon and further studied using our highly flexible GUI controlled irradiator.

Conclusion

The public is exposed to more ionizing radiation now than they ever have been. This is due in part to the increasing use of radionuclides in medicine. It is therefore important to understand how chronic and variable low dose rates affect biological tissue. The GUI controlled ^{137}Cs gamma ray irradiator described herein is capable of generating meaningful and clinically relevant dose-rate patterns that result from the administration of internal radionuclides. The device's utility in studying the biological effects of low dose rate radiation can also be applied to the field of radiation protection, where a consensus on the linear no-threshold model has yet to be achieved. In concert with the sharing policies promoted by the National Institutes of Health, we welcome requests for collaborative studies to access the manifold capabilities of this irradiator.

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Figure 1.
Low dose rate irradiator with mercury attenuator system.

Figure 2.

Screenshot of the graphic user interface (GUI) for delivering a constant dose rate pattern. The parameters have been entered as shown: $r_0 = 5$ cGy/hr and $t = 12$ h. The dose of 60 Gy was automatically calculated by the GUI. The distance from the top of the irradiator at which the sample should be placed is indicated as 507 mm. Calibration curves for the irradiator appear in the upper right corner and aid the user to plan the radiation delivery. Dose rate, dose, and mercury thickness are plotted as a function of time in the lower left, middle, and right regions of the GUI, respectively. Red lines denote the planned delivery. The black line in the dose rate plot shows the minimum dose rate that can be delivered to a sample at distance 507 mm from the source (e.g. all Hg in attenuator). The pink line in the Hg thickness plot is a planning aid that shows the maximum permissible mercury thickness.

Figure 3.

Screenshots of the graphic user interface for different variable dose rate patterns. The solid red lines represent planned dose rate profiles. Overlying purple stars represent the dose rate as the experiment progresses. **A.** beginning of an exponential increase experiment with $d=315$ mm, $r_0=0.109$ cGy/hr, $T_d=1.83$ hr, $t=12$ hr, and calculated $D=26.797$ cGy. **B.** first third of an exponential decrease experiment with $d=126$ mm, $r_0=40$ cGy/hr, $T_d=13.22$ hr, $t=73$ hr, and calculated $D=744.886$ cGy. **C.** two component exponential pattern with $d=1152$ mm, $r_0=6$ cGy/hr, $a=1$, $b=0.99$, $T_{d1}=8$ hr, $T_{d2}=1$ hr, $T_i=4$ hr, $t=24$ hr, and $D=26.797$ cGy.

Figure 4.

Predicted and measured dose rates of GUI-controlled delivery of different dose rate profiles:

A. initial dose rate of 0.11 cGy/hr and exponential increase half-time of 1.83 hr. **B.** initial dose rate of 10.2 cGy/hr and exponential decrease half-time of 1.83 hours. Experiment was intended to simulate decay of ^{18}F , a common diagnostic radionuclide. **C.** initial dose rate of 40 cGy/hr and exponential decrease half-time of 13.22 hr. Experiment was intended to simulate decay of ^{123}I , a common diagnostic radionuclide. **D.** *extrapolated* initial dose rate of 0.06 cGy/hr, exponential increase half-time of 4 hr, and exponential decrease half time of 8 hr. Experiment was intended to demonstrate capacity of irradiator to simulate dose rate profiles following radionuclide uptake and decay in an organ.

Table 1

Dose rates attainable at different positions within the irradiator on 1/12/2012[†].

Position in Irradiator (mm from source)	Maximum dose rate 0 mm Hg, 0× lead* (cGy/hr)	Minimum dose rate 35.8 mm Hg, 0× lead* (cGy/hr)	Minimum dose rate 35.8 mm Hg, 100× lead** (cGy/hr)
126	40.2	0.32	0.0032
200	20.2	0.16	0.0016
400	7.22	0.057	0.00057
600	3.95	0.031	0.00031
800	2.56	0.021	0.00021
1000	1.85	0.015	0.00015
1194	1.42	0.011	0.00011

[†] Three significant figures are provided at high dose rates whereas only two significant figures are provided for the lower dose rates to reflect the increase errors associated with low dose rate measurements.

* 0× lead implies that no lead attenuators were inserted between the ¹³⁷Cs source and sample.

** 100× lead implies that 100 fold lead attenuators were inserted between the ¹³⁷Cs source and sample.

Table 2

RadNuc GUI error messages and their causes/solutions.

Error Message	Cause/Solution
Dose Rate is too high to be achieved at this position in the irradiator.	Function that returns mercury thickness returns a value less than zero. Decrease the value of the dose rate.
Dose Rate is too low to be achieved at this position in the irradiator.	Function that returns mercury thickness returns a value greater than 35.8 mm. Increase the value of the dose rate.
Please enter exactly two of the three data fields.	Enter only two of dose, initial dose rate, and time.
Cannot achieve a dose rate of [offending dose rate] cGy/hr within this attenuator configuration. The maximum possible dose rate is [max dose rate in irradiator] cGy/hr and the minimum possible dose rate is [min dose rate in irradiator] cGy/hr.	Requested dose rate pattern involves a dose rate not achievable in the irradiator. Change values.
Please enter the dose rate half time.	No half time has been entered. Please enter.
Please enter a positive value for the dose rate half time.	A zero or negative half-life was entered on the exponential increase/decrease tab.
Dose desired cannot be achieved given the initial rate and the half time.	The initial dose rate and decrease half time cannot be provided by the irradiator. Change values.
Cannot achieve that range of dose rates (high = [high dose rate] cGy/hr and low = [low dose rate] cGy/hr) at a single position within the irradiator. You have requested a [high/low] fold change in dose rate. Mercury movement only allows up to a 125 fold change in Dose Rate.	User requested a dose rate pattern that features a greater than 125-fold difference in high and low dose rates. Change values.
Please enter values for a and b.	Values were not entered for a and b. Please enter.
Please enter a value for a such that $0 < a \leq 1$.	Value of a is below 0 or above 1. Change value.
Please enter a value for b such that $0 < b \leq 1$.	Value of b is below 0 or above 1. Change value.
Please enter a value for T_{d1} .	Value of T_{d1} has not been entered. Please enter.
Please enter a value for T_{d2} .	User has entered a value for a other than 1 and has not entered a second decrease half time.
Please enter values for T_{d1} and T_{d2} .	User has entered a value for a other than 1 or 0 and has not entered both T_{d1} and T_{d2} decrease half times on the multi-component exponential tab.