



The Nuclear Medicine Patient as a Line Source: The Source Length Is Certainly Not the Patient Height, But It Is a Reasonable Approximation

David Broggio

► To cite this version:

David Broggio. The Nuclear Medicine Patient as a Line Source: The Source Length Is Certainly Not the Patient Height, But It Is a Reasonable Approximation. *Health Physics*, 2022, 123 (3), pp.208-217. 10.1097/HP.0000000000001587 . hal-03863501

HAL Id: hal-03863501

<https://hal.science/hal-03863501>

Submitted on 16 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

The Nuclear Medicine Patient as a Line Source: The Source Length Is Certainly Not the Patient Height, But It Is a Reasonable Approximation

David Broggio¹

Abstract—Nuclear medicine patients are a source of exposure and should receive instructions to restrict contact time with different categories of people. The calculation of the restriction time requires that the dose rate at a given distance, known from an initial measurement and a whole-body retention function, can be extrapolated at other distances. As a basis for this extrapolation, it has been suggested to consider the patient as a line source. However, the validity of this suggestion is based on a few studies and limited measurement distances. We collected from the literature dose rates of nuclear medicine patients measured at different distances and investigated the robustness of the line source model. The cases of ¹⁸F-FDG exams, ^{99m}Tc bone scan exams, and ¹³¹I for hyperthyroidism treatment and remnants ablation were considered. The data were pooled, different cases of measurement time after administration were considered, and the data were fitted according to the line source model in which the half patient thickness was introduced. It was found that the line source model fits well the data put with a source length that is radionuclide-specific and significantly different from the standard adult height. However, considering a standard source length of 176 cm and neglecting the patient thickness induced at maximum an overestimation by a factor of 2.5 when extrapolating from 1 m to 10 cm. Such an overestimation is not of considerable importance in the calculation of contact restriction times.

Health Phys. 123(3):208–217; 2022

Key words: dose, external; exposure, population; nuclear medicine; radiation, medical

INTRODUCTION

NUCLEAR MEDICINE patients are a source of exposure for members of the public, their relatives, and co-workers. In Europe and in the United States, it is mandatory to deliver instructions to those patients before their release in order to limit the exposure of members of the public (Council of the European Union 2014; US NRC 2021). These instructions usually prescribe avoiding contact with categories of people such as co-workers, children, pregnant women, family members, and co-travelers in public transport for a given period. After this period, the exposure of the contact person falls below a dose limit fixed by national regulations.

These instructions are necessarily based on exposure scenarios that define the contact time and distance for each category of contact person. Several scenarios differing by the distance and contact time or dose constraint have been proposed (O'Doherty et al. 1993; Zanzonico et al. 2000; Carlier et al. 2004). Whatever the scenario, if the dose rate of the patient is known, the restriction time can be calculated (Cormack and Shearer 1998; Zanzonico et al. 2000; Carlier et al. 2004). General guidance giving the restriction time as a function of measured dose rate or injected activity has been issued (European Commission 1998; ICRP 2004; IAEA 2009). As pointed out by several authors (Cormack and Shearer 1998; Zanzonico et al. 2000; Liu et al. 2015a; Han et al. 2021), it is better to base the instructions on the measured patient's dose rate; otherwise, one has to rely on default dose rates that do not take into account the high interpatient variability. Illustrative examples of inter-patient variability of retention can be found in Berg et al. (1996), Hänscheid et al. (2006), and Taprogge et al. (2021).

Usually the dose rate is measured at a fixed distance—in many cases at 1 m (European Commission 1998; Al-Haj et al. 2007; Dos Santos et al. 2015). To assess the exposure rate at the other distances defined by the exposure scenario, one thus needs a “scaling law” to compute the exposure at these distances from the 1-m exposure. The scaling law,

¹Institut de Radioprotection et de Sécurité Nucléaire, IRSN/PSE-SANTE/SDOS/LEDI, BP-17, Fontenay-aux-Roses, France.

The author declares no conflicts of interest.

For correspondence contact the author at the above address, or email at david.broggio@irsn.fr.

(Manuscript accepted 23 March 2022)

Supplemental digital content is available in the HTML and PDF versions of this article on the journal's website www.health-physics.com. 0017-9078/22/0

Copyright © 2022 The Author(s). Published by Wolters Kluwer Health, Inc. on behalf of the Health Physics Society. This is an open-access article distributed under the terms of the Creative Commons Attribution-Non Commercial-No Derivatives License 4.0 (CCBY-NC-ND), where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.

DOI: 10.1097/HP.0000000000001587

except at long distances or for very specific cases, is certainly not the inverse square law, as pointed out many times (Chiesa et al. 1997; Cormack and Shearer 1998; Sparks et al. 1998). To compute the exposure rate correctly, particularly for close contact distances, it has been suggested to consider the patient as a line source (Castronovo et al. 1982; Siegel et al. 2002). It should be acknowledged that despite this, the approach is usually accepted (Matheoud et al. 2004; De Carvalho et al. 2011; D'Alessio et al. 2015; Liu et al. 2015b). The experimental evidences for such an approach are limited to a few studies (Willegaignon et al. 2007; Yi et al. 2013; D'Alessio et al. 2015) and limited to a small number of short distances or a single distance (Liu 2015b).

The aim of this work was to investigate further the robustness of the patient line source model. For that purpose, we collected measured exposure rate data from the literature, pooled them, and fitted the line source model to the experimental data. In particular, the patient diameter was taken into account through an additional fitting parameter, and the source length that best fitted the data was obtained. The consequences of using the standard adult height for the source length rather than the best fitting length was then investigated. The cases of ^{18}F -FDG exams, $^{99\text{m}}\text{Tc}$ bone scan exams, and ^{131}I for hyperthyroidism treatment and remnants ablation were considered. This study aimed at investigating the trend of the dose rate variation with distance, not its absolute value. As such, if it can be assumed that the dose rate is known at a given distance, the relevant quantity is the scaling factor enabling the prediction of the dose rate at other distances.

MATERIALS AND METHODS

Line source model

The dose rate (\dot{D}) due to a line source of length l at a point situated at distance d from the line and at half the source length is given by Siegel et al. (2002) and Cember and Johnson (2009):

$$\dot{D}(d) = k \frac{\text{atan}\left(\frac{l}{2d}\right)}{\frac{dl}{2}}. \quad (1)$$

The k factor takes into account the source activity and the gamma ray constant of the radionuclide (Cember and Johnson 2009), since hereafter we are interested in the dose rate trend as a function of the distance and not its magnitude, so the proportionality factor is not of importance.

Usually, the dose rates of patients are measured so that the body surface is taken as the origin of distances. Thus, to avoid divergence at the origin and to model the line source at the center of the patient's body, it is more suitable to consider the following relationship:

$$\dot{D}(d) = k \frac{\text{atan}\left(\frac{l}{2(d+d_0)}\right)}{\frac{(d+d_0)l}{2}}. \quad (2)$$

The d_0 parameter thus accounts for the patient half-thickness and d for the distance measured from the patient's body. Hereafter, d_0 is taken as a free parameter that is fitted from experimental data, as well as the source length.

Experimental data processing

The line source model is of interest since it enables one to calculate the dose rate at a given distance from a reference measurement. As explained in the introduction and evidenced from the collected experimental data (see below), most measurements are usually taken at 1 m. We thus considered relative dose rates normalized at 100 cm. The relative dose rate (\dot{D}_r) was thus defined as:

$$\dot{D}_r(d) = \frac{\dot{D}(d)}{\dot{D}(100)}. \quad (3)$$

The relative dose rate thus only depends on the distance d_0 and source length.

Having relative dose rates obtained from measurement (\dot{D}_r^{meas}) at several distances (d_i), one can find the source length and d_0 that best describe the measurement data. For that purpose, we minimized the chi-square (Wolberg 2006):

$$\chi^2 = \sum_i \frac{(\dot{D}_r(d_i) - \dot{D}_r^{\text{meas}}(d_i))^2}{\sigma_i^2}. \quad (4)$$

The chi-square minimization and calculation of the 1-sigma uncertainty on fitted parameters were carried out with the mpfit library (Markwardt 2009). The uncertainties σ_i on measured data were fixed as explained below.

Collected data

We collected measured dose rate data of patients from the literature and considered the cases of ^{18}F -FDG exams, $^{99\text{m}}\text{Tc}$ bone scan exams, treatment of hyperthyroidism with ^{131}I , and ablation treatment of thyroid remnants with ^{131}I .

The criteria for retaining the studies were as follows:

- At least two measurement distances were provided, with one distance being 1 m;
- Measurements were performed at the thorax or abdomen level;
- The time of measurement was given;
- Language was English, French, German, or Spanish; and
- Full text was available.

As a consequence, some potentially interesting studies were disregarded because the measurement position was not described, because the reported measurement consisted of the maximum dose rate obtained during vertical displacement of the measurement device, or because the dose rates were taken at the thyroid level. For ^{131}I treatment, we disregarded

measurement at the thyroid level to avoid a possible bias of the final data set and because measurement at this position does not comply with the recommendations of measuring Hp(10) at the thorax level (ICRU 2020).

Data were processed as follows:

1. For each study, the reported dose rates were normalized to obtained relative dose rates (eqn 3);
2. The uncertainty on the normalized dose rate was fixed: from reported uncertainties, readings of error bars or recalculation from raw data. For data extraction from figures, WebPlotDigitizer (Rohatgi 2020) was used. If none of these methods were applicable, a default uncertainty of 25% was applied to measurements at a given distance, thus 35% for the normalized value. Uncertainties could be retrieved for 110 of 146 data points, and the 25% corresponded to a typical value of quoted or reported uncertainties even if uncertainties as large as 100% or as low as 5% were sometimes reported;
3. Normalized dose rates were grouped according to a measurement time category (for example “immediate” or “24 h”); and
4. For each distance in a measurement time category, the weighted mean and weighted standard deviations were calculated, using the number of measured patients for the sample size (Dunn and Clark 2009).

At this stage the chi-square minimization was performed with the weighted means and standard deviations.

¹⁸F-FDG data set. We retrieved 15 studies (Chiesa et al. 1997; Cronin et al. 1999; Benatar et al. 2000; Pant and Senthamizhchelvan 2006; Gomes et al. 2010; Demir et al. 2011; Sudbrock 2011; Quinn 2012; Kim 2013; Yi 2013; Uhrhan 2014; Fayad et al. 2015; Choi et al. 2018; Al-Aamria et al. 2019; Günes et al. 2019) providing the required data; the number of patients per study was between 6 and 152. We defined two categories of measurement time: “immediate” and “1 h.” The first one is for measurements taken immediately after injection or maximum 15 min after injection, and the second one is for measurements taken between 50 min and 2 h after injection. In the “immediate” category, eight measurement distances (excluding the 100 cm case) were available, between 0 and 500 cm. Eight measurement distances between 0 and 200 cm were available for the “1 h” category.

The source of data, measurement times, number of patients, and normalized dose rates as a function of distance are reported in Table 1. The average values and standard deviations used for fitting the source line model are also given in Table 1 for each category of measurement time. The values at 100 cm are reported for clarity in Table 1, but they are not taken into account in fitting the source line model.

^{99m}Tc bone scan data set. We retrieved 16 studies (Castronovo 1991; Mountford et al. 1991; Konishi et al. 1994; Havlik et al. 1996; Greaves and Tindale 1999; Gomez-Palacios et al. 2005; Lemoine et al. 2011; Sudbrock et al. 2011; Bartlett 2013; Kim et al. 2013; Stenstad et al. 2014; Fayad et al. 2015; Morán et al. 2016; Javed et al. 2017; Ohiduzzaman et al. 2019; Das and Mondal 2020) providing the required data. The number of patients per study was between 6 and 145. We defined three categories of measurement time: “immediate”, “3 h” and “24 h.” The first category was for measurements taken at maximum 30 min after injection, the second one for measurements between 2 and 4 h, the last one for measurements at 24 h. The numbers of available measurement distances in these categories are 6 (immediate), 8 (3 h) and 3 (24 h). Measurement distances varied between 0 and 200 cm.

The source of data, measurement times, number of patients, normalized dose rates as a function of distance, average values, and standard deviations used for fitting are provided as Supplemental Digital Content (Table S1: <http://links.lww.com/HP/A218>).

¹³¹I treatment of hyperthyroid patients. We retrieved five studies (O'Doherty et al. 1993; Demir et al. 1996; Muhammad et al. 2006; Sudbrock et al. 2009; Liu et al. 2015a) providing the required data, and the number of patients per study was between 7 and 72. We defined three categories of measurement time: “day 0,” “day 3,” and “day 7.” The first category (five studies) was for measurements taken immediately after injection or on the injection day, the second one for measurements taken 3 d after injection (three studies), and the last one for measurements taken 7 or 8 d after injection (two studies). The numbers of available measurement distances in these categories are 8 (day 0), 5 (day 3), and 4 (day 7). Measurement distances varied between 0 and 500 cm.

The source of data, measurement times, number of patients, normalized dose rates as a function of distance, average values, and standard deviations used for fitting are provided as Supplemental Digital Content (Table S2: <http://links.lww.com/HP/A218>).

¹³¹I treatment of thyroid remnants. We retrieved seven studies (Barrington et al. 1996; Willegaignon et al. 2007; Sudbrock et al. 2009; Yi et al. 2013; Liu et al. 2014; Dehkordi et al. 2017; Mat Nawi et al. 2020) providing the required data; the number of patients per study was between 3 and 231. We defined three categories of measurement time: “day 0,” “day 1,” and “day 2.” The first category (six studies) was for measurements taken immediately after injection or on the injection day, the second and third categories each included data from three studies. The numbers of available measurement distances in these categories are 13 (day 0), 4 (day 1), and 4 (day 2). Measurement distances varied between 0 and 700 cm.

Table 1. Summary of collected data for ^{18}F -FDG exams. The upper part of the table gives the reference study, the measurement time, the number of patients, and the relative dose rate at the measurement distance. The lower part gives the normalized dose rates and standard deviations used for fitting the model in each of the measurement time categories.

Reference	Measurement time	No. of patients	Distance (cm)									
			0	10	25	30	50	75	100	150	200	500
Chiesa et al. 1997	50 min	23	14.65			5.15			1			
Cronin et al. 1999	2 h	75		6.60			2.55		1		0.36	
Benatar et al. 2000	immediate	115		8.53			2.73		1		0.40	
Pant and Senthazhivelvan 2006	immediate	64	20.92				3.10		1		0.43	
Gomes et al. 2010	1 h	30			5.47		2.63	1.56	1	0.58	0.37	
Demir et al. 2011	1 min	30		4.79	3.91		2.61		1		0.36	
	87 min	30		6.62	4.54		2.69		1		0.31	
Sudbrock et al. 2011	immediate	21	20.00				2.67		1		0.33	0.07
Quinn et al. 2012	77 min	152	9.31			3.79			1			
Kim 2013	1 h 30	10				4.49	2.42					
Yi 2013 ^a	15 min	52				4.56			1			
Uhrhan et al. 2014	immediate	37					2.44		1		0.31	
Fayad et al. 2015	1 h 30	6	13.15				2.64		1			
Choi et al. 2018	1 h 30	30	17.00	9.91		4.55	2.63		1			
Al-Aamria et al. 2019	immediate	70				3.48	1.96		1		0.38	
	120 min	70				4.62	2.38		1		0.38	
Güneş et al. 2019	immediate	29	17.96				2.95		1	0.46	0.30	
	70 min	29	10.41				2.36		1	0.56	0.30	
						immediate						
		mean	20.49	7.76	3.91	3.94	2.62	NA	1	0.46	0.38	0.067
		SD	4.79	2.90	1.45	2.25	0.91	NA	0	0.19	0.15	0.025
						one hour						
		mean	10.96	7.34	5.01	3.07	2.52	1.56	1	0.57	0.35	NA
		SD	4.14	2.43	1.22	1.60	0.94	0.10	0	0.12	0.15	NA

^aExperimental values deduced from reported calculations.

Table 2. Summary of line source model fitted parameters, their uncertainties, and chi-square statistics.

Case	Meas. Time	<i>l</i> (cm)	<i>d</i> ₀ (cm)	[chi] ² /ndf	p([chi] ²)
¹⁸ F-FDG	immediate	347 ± 194	8.1 ± 3.2	0.12	0.994
	one hour	116 ± 715	28.9 ± 104	0.19	0.979
^{99m} Tc bone scan	immediate	644 ± 657	6.3 ± 3.1	0.21	0.932
	3 hours	230 ± 216	12.8 ± 13	0.25	0.959
	24 hours	110 ± 1957	22.8 ± 265	0.06	0.806
	day 0	208 ± 78	3.6 ± 1.1	0.32	0.929
¹³¹ I hyperthyroidism treatment	day 3	455 ± 662	2.3 ± 1.1	1.64	0.177
	day 7	93 ± 4806	20.6 ± 719	0.24	0.791
	day 0	348 ± 80	3 ± 1	0.2	0.998
¹³¹ I remnant ablation	day 1	849 ± 4184	3.2 ± 10	0.3	0.748
	day 2	820 ± 3453	4.5 ± 13	0.05	0.952

The source of data, measurement times, number of patients, normalized dose rates as a function of distance, average values, and standard deviations used for fitting are provided as Supplemental Digital Content (Table S3: <http://links.lww.com/HP/A218>).

RESULTS AND DISCUSSION

Fitting of the line source model

The fitted parameters (i.e., the source length and patient half thickness, *d*₀, and their 1-sigma uncertainty) are reported in Table 2 for the four medical procedures and the categories of measurement time defined above. As an indicator of the goodness of fit, the ratio of the chi-square to the number of degrees of freedom is also reported in Table 2, as well as the chi-square probability.

In the case of the ¹⁸F-FDG exams, the source lengths for the two measurement time categories were 347 cm (immediate measurements) and 116 cm (measurements around 1 h); the *d*₀ parameters were 8 cm (immediate measurements) and 29 cm (measurements around 1 h). Even if the p-values associated with the chi-square are statistically significant in both cases, in the case of measurements around 1 h, the uncertainty on fitted parameters is greater than the parameters. Fig. 1 shows the result of the fitting for the categories of “immediate” measurements. Fitting results for the measurements around 1 h are shown as Supplemental Digital Content (Fig. S1: <http://links.lww.com/HP/A218>).

In the case of ^{99m}Tc bone scan exams, the fitted source lengths were 644 cm, 229 cm, and 110 cm for, respectively, the time categories “immediate,” “3 h,” and “24 h.” The *d*₀ parameters varied between 6 and 23 cm depending on the measurement time. For the measurements around 24 h, the

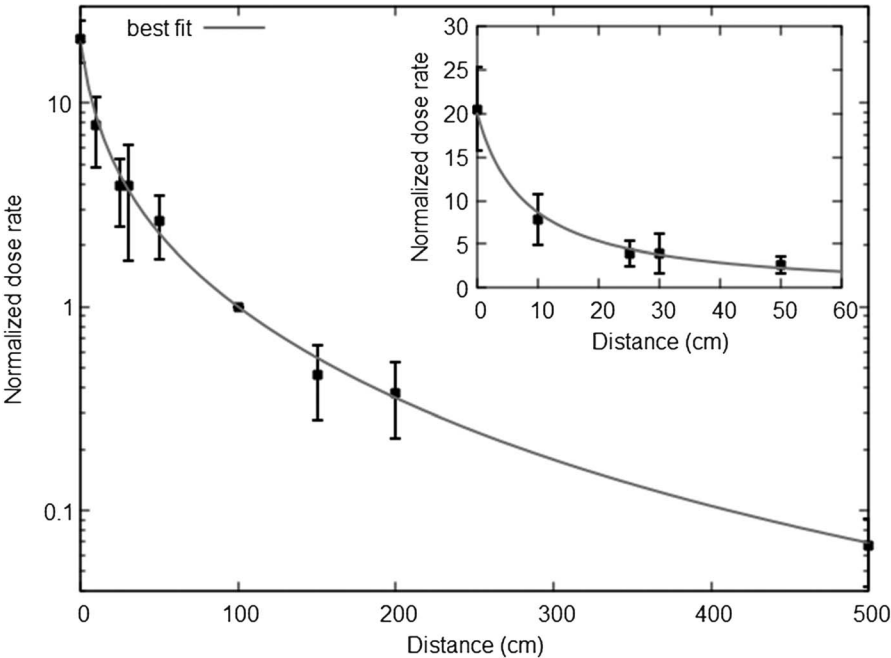


Fig. 1. Experimental and fitted normalized dose rate as a function of distance for immediate measurements after ¹⁸F-FDG administration.

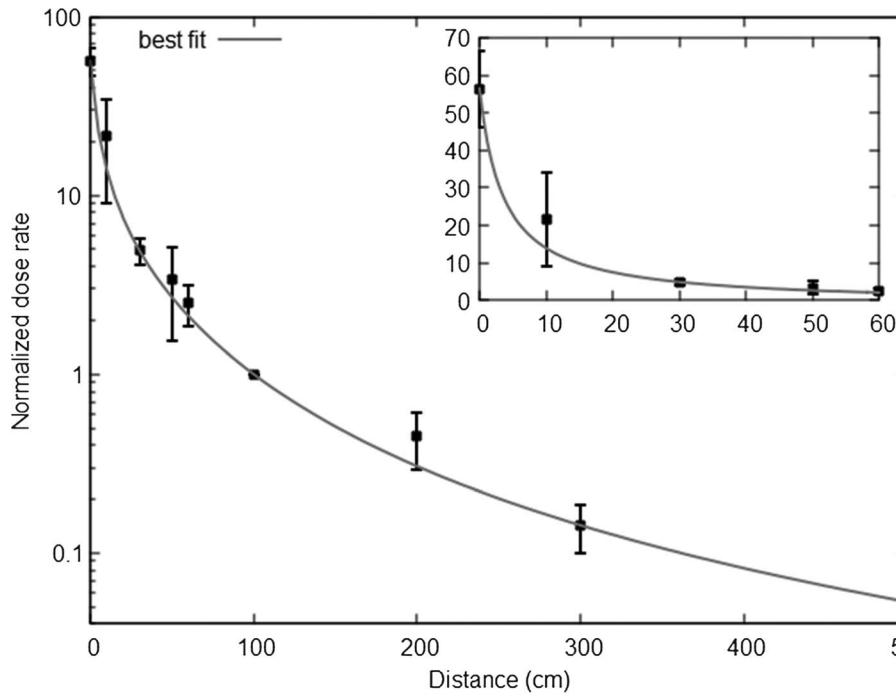


Fig. 2. Experimental and fitted normalized dose rate as a function of distance for immediate measurements after administration of ^{131}I for hyperthyroidism treatment.

uncertainties on fitted parameters were greater than the parameters. For the two other categories, the uncertainty was of the order of magnitude of the parameters. Fitting results for the three measurement time categories are shown as Supplemental Digital Content (Fig. S2: <http://links.lww.com/HP/A218>).

In the case of hyperthyroidism treatment with ^{131}I , the fitted source lengths varied between 92 and 454 cm, and d_0 varied between 2.3 and 20 cm. Only in the case of measurements at the treatment day, the fitted parameters had an uncertainty smaller than their values. Fig. 2 shows the result of the fitting for the categories of measurements on the treatment day. Fitting results for the two other cases of measurement time are shown as Supplemental Digital Content (Fig. S3: <http://links.lww.com/HP/A218>).

In the case of remnant ablation with ^{131}I , the fitted source lengths varied between 348 and 850 cm, and d_0 varied between 3 and 4.5 cm. Only in the case of measurements at the treatment day, the fitted parameters had an uncertainty smaller than their values. Fitting results for the three measurement time categories are shown as Supplemental Digital Content (Fig. S4: <http://links.lww.com/HP/A218>).

Consequences of using a default line source model

If the fitted parameters of the line source model are unknown, a reasonable choice is to consider a standard height and disregard the parameter d_0 (default model). Considering that a dose rate measurement is carried out at 1 m, one can compare the dose rate scaling factors to other distances

using the default model or the model including fitted parameters. Hereafter, we calculated the scaling factors for the distances of 10 cm, 30 cm, and 200 cm. We selected 176 cm for the standard height, the l and d_0 parameters obtained for immediate measurements (^{18}F -FDG), 3 h ($^{99\text{m}}\text{Tc}$ bone scan exam), and day 0 (^{131}I treatment of hyperthyroidism and remnant ablation). These choices corresponded to the most significant fits.

The resulting scaling factors are shown in Table 3 as well as their ratios. The default model produced a scaling factor greater than with the fitted model when extrapolating from 100 cm to shorter distances. The overestimation factor was between 1.4 (hyperthyroidism treatment) and 2.4 ($^{99\text{m}}\text{Tc}$) when going from 100 to 10 cm. When going from 100 to 30 cm, the overestimation factor was between 1.2 and 1.5. In the case of extrapolation from 100 to 200 cm, the default model gave an underestimation of the dose rate; the factor was between 0.8 and 0.9.

Fig. 3 shows the ratio of scaling factors (default model over fitted model) for distances between 10 and 250 cm. The relative difference between the default and fitted model was within 25% for distances between 20 and 250 cm (hyperthyroidism treatment) or between 50 and 250 cm (^{18}F -FDG). The relative difference was less than 50% for distances as short as 10 cm (hyperthyroidism treatment) or 20 cm.

One can also consider a scaling factor based on the inverse square law. The ratio of the scaling factors for the fitted model and inverse square law model is also plotted on Fig. 3. The inverse square law was within 25% of the

Table 3. Comparison of dose rate scaling factors from 100 cm to other distances when default or fitted model parameters are used.

	Scaling factor : 100 to 10 cm		Scaling factor : 100 to 30 cm		Scaling factor : 100 to 200 cm		Default/Fitted	Default	with fitted parameters	Default/Fitted	Default	with fitted parameters	Default/Fitted	Default	with fitted parameters	Default/Fitted	
	Default		with fitted parameters		Default/Fitted												
¹⁸ F-FDG	20.2		8.6		2.3			5.7		1.5		3.8		0.29		0.36	0.81
^{99m} Tc	20.2		8.6		2.4			5.7		1.4		4.0		0.29		0.33	0.87
¹³¹ I Hyperthyroidism	20.2		13.9		1.4			5.7		1.2		4.9		0.29		0.31	0.94
¹³¹ I Remnant ablation	20.2		11.4		1.8			5.7		1.4		4.2		0.29		0.35	0.83

fitted model for distance between 70-160 cm (¹⁸F-FDG) or between 60–250 cm (hyperthyroidism treatment). The inverse square law was within 50% of the fitted model for distances between 50 and 250 cm.

DISCUSSION

As evidenced by the fit results, the trend of the dose rate variation with distance from nuclear medicine patients is well described by the line source model. However, the source length that best describes the data is certainly not the patient height. For some measurement times, the fitted source length is associated with a large uncertainty, but when the uncertainty is smaller, the source length remains greater than the standard adult height. The *d_o* that was introduced in the line source model is of the order of 5 cm. Even if an order of magnitude of 10 cm would have been expected, one can consider the result as consistent with the half thickness of patients. The large uncertainties on fitted parameters, especially the source length, have two origins. First, the relatively large error bars on data points are dominated by the inter-study variations rather than by the uncertainty from a given study. Consequently, having affected a typical uncertainty of 25% to data that were published without uncertainty, even if disputable, is certainly of minor concern. Second, large variations on the source length parameter do not produce large variation on the dose rate. This last effect is illustrated by the ratio of scaling factors in Table 3 and Fig. 3. When the source length is decreased from around 350 cm to 176 cm, the dose rate is modified to less than 25%, except for distances shorter than 30-50 cm.

This study does not pretend to be exhaustive even if efforts have been made to retrieve as many data as possible. Measurement distances have been collected from contact to several meters and the fit performed over considerably more distances than previously; therefore, the patient line source model validity is reinforced. Radiopharmaceuticals used for diagnostics are, of course, not a big issue in terms of public exposure by patients, but they enable testing of the validity of the model.

If radionuclide-specific or measurement-time specific parameters are not available, it has been shown that using default parameters does not induce errors that are too large in the calculation of dose rate scaling factor. Of course, for short contact distances, the default parameter can lead to an overestimation of the dose rate by a factor of 2. However, the dose rate is ultimately used for the calculation of a restriction time, which is a logarithm function of the dose rate (see Carlier et al. 2004, for example). As a consequence, overestimation of the restriction time should be minimal.

A robust scaling factor is needed to calculate meaningful restriction times, but it is not the sole parameter that affects the relevance of calculations. The biokinetic

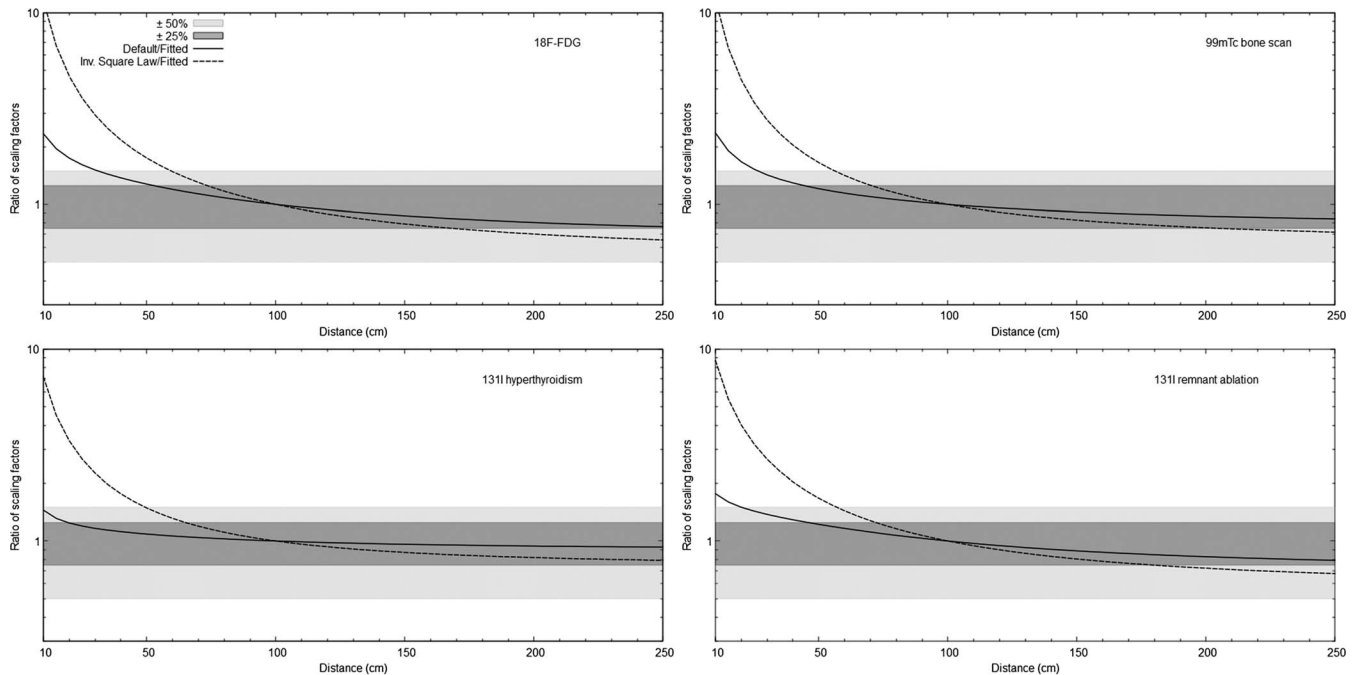


Fig. 3. Ratio of scaling factors as a function of distances for the four medical procedures considered. The scaling factors considered are based on the line source model with fitted parameters, the line source model with default parameters, and the point source approximation.

parameters describing the whole-body retention (Liu et al. 2014) are also of importance and should be chosen with care. In Liu et al. (2015b), mathematical phantoms and a static activity distribution have been used to calculate dose rate at 30 and 100 cm by Monte Carlo simulations. It was concluded that the line source model is a good approximation for ^{99m}Tc , ^{18}F , and ^{131}I used for remnant ablations. In Han et al. (2013), more realistic adult and child phantoms were used to compute dose rates with static activity distribution for hyperthyroid patients and patients with differentiated thyroid cancer. This study confirmed that the point source approximation is too conservative but also that the activity distribution inside the patient strongly affected the calculation results. Further investigation by Monte Carlo calculations might be of interest, for example, by carrying out dose rate calculations at several time points according to the radiopharmaceutical biokinetic model (Lamart et al. 2009; Chen et al. 2016); however, the confidence in the calculation would not be stronger than the confidence in the biokinetic model. Experimental measurements of dose rate or whole-body retention after the radiopharmaceutical administration are thus also of importance.

When patients are released a day or more after the treatment, it would be more relevant to base the scaling factor on measurement performed at the release date. However, we have evidenced that most of the data have been collected just after injection and that these data provide the more robust fits. As discussed above, using a scaling based on a standard height is a good approximation, and this should apply whatever the time after injection.

CONCLUSION

Collecting data from the literature enabled us to show that the patient line source model correctly describes the trend of the dose rate variation with distance of nuclear medicine patients. Model fitting has been carried out over many distances and for four treatment cases, improving the confidence in the model. Even if the source length that best described the data did not correspond to the standard adult height, using a standard height induced acceptable approximation, especially if the goal is to calculate contact restriction times.

The conclusion of this study cannot strictly apply to radionuclides that have not been studied, but it is difficult to imagine a radiopharmaceutical distribution so particular that it would imply that the patient line source model would become inapplicable.

REFERENCES

- Al-Aamria M, AL-Balushia N, Bailey D. Estimation of radiation exposure to workers during [^{18}F] FDG PET/CT procedures at Molecular Imaging Center, Oman. *J Med Imag Radiat Sci* 50:565–570; 2019. DOI:10.1016/j.jmir.2019.05.009.
- Al-Haj AN, Lagarde CS, Lobriguito AM. Patient parameters and other radiation safety issues in ^{131}I therapy for thyroid cancer treatment. *Health Phys* 93:656–666; 2007. DOI:10.1097/01HP0000270274662467e.
- Barrington SF, Kettle AG, O'Doherty MJ, Wells CP, Somer EJR, Coakley AJ. Radiation dose rates from patients receiving iodine-131 therapy for carcinoma of the thyroid. *Eur J Nucl Med* 23:123–130; 1996. DOI:10.1007/BF01731834.

- Bartlett ML. Estimated dose from diagnostic nuclear medicine patients to people outside the nuclear medicine department. *Radiat Protect Dosim* 157:44–52; 2013. DOI:10.1093/rpd/nct119.
- Benatar NA, Cronin BF, O'Doherty MJ. Radiation dose rates from patients undergoing PET: implications for technologists and waiting areas. *Eur J Nucl Med* 27:583–589; 2000.
- Berg GEB, Michanek AMK, Holmberg ECV, Fink M. Iodine-131 treatment of hyperthyroidism: significance of effective half-life measurements. *J Nucl Med* 37:228–232; 1996.
- Carlier T, Lisbona A, Kraeber-Bodere F, Ansquer C, Couturier O. Practical recommendations for outpatients after differentiated thyroid carcinoma treatment with iodine-131. *Radioprotection* 39:481–492; 2004. DOI:10.1051/radiopro:2004012.
- Castronovo FP Jr, Beh RA, Veilleux NM. Dosimetric considerations while attending hospitalized I-131 therapy patients. *J Nucl Med Technol* 10:157–160; 1982.
- Castronovo FP. Time dependent radiation exposures surrounding technetium-99m MDP patients. *J Nucl Med Technol* 19:182–184; 1991.
- Cember H, Johnson TE. Introduction to health physics. New York: McGraw Hill; 2009.
- Chen Y, Qiu R, Li C, Wu Z, Li J. Construction of Chinese adult male phantom library and its application in the virtual calibration of in vivo measurement. *Phys Med Biol* 61:2124–2144; 2016. DOI:10.1088/0031-9155/61/5/2124.
- Chiesa C, De Sanctis V, Crippa F, Schiavini M, Fraigola CE, Bogni A, Pascali C, Decise D, Marchesini R, Bombardieri E. Radiation dose to technicians per nuclear medicine procedure: comparison between technetium-99m, gallium-67, and iodine-131 radiotracers and fluorine-18 fluorodeoxyglucose. *Eur J Nucl Med* 24:1380–1389; 1997. DOI:10.1007/s002590050164.
- Choi B, Ha S, Sung C, Lee SH, Kim H, Oh J, Lee JL, Kim J, Ryu JS. Estimation of effective radiation dose to medical personnel, based on dose rates in patients who have undergone ^{18}F -FDG PET/CT scans. *J Nucl Med* 59(Suppl1):S22; 2018.
- Cormack J, Shearer J. Calculation of radiation exposures from patients to whom radioactive materials have been administered. *Phys Med Biol* 43:501–516; 1998. DOI:10.1088/0031-9155/43/3/003.
- Council of the European Union. Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation. *J Eur Union L* 59:1–73; 2014.
- Cronin B, Marsden PK, O'Doherty MJ. Are restrictions to behaviour of patients required following fluorine-18 fluorodeoxyglucose positron emission tomographic studies? *Eur J Nucl Med* 26:121–128; 1999. DOI:10.1007/s002590050367.
- D'Alessio D, Giliberti C, Benassi M, Strigari L. Potential third-party radiation exposure from patients undergoing therapy with ^{131}I for thyroid cancer or metastases. *Health Phys* 108:319–325; 2015. DOI:10.1097/HP0000000000000210.
- Das PK, Mondal A. Measurement of the dose rate resulted from scintigraphy patient at INMAS. *Pabna University of Science and Technology Studies* 4:7–11; 2020.
- De Carvalho AB Jr, Stabin MG, Siegel JA, Hunt J. Comparison of point, line and volume dose calculations for exposure to nuclear medicine therapy patients. *Health Phys* 100:185–190; 2011. DOI:10.1097/HP0b013e3181eac3f8.
- Dehkordi FJ, Rasuli B, Mahmoud-Pashazadeh A. An evaluation of deviation from the International Atomic Energy Agency-International Commission on Radiological Protection proposed equation for calculation of radiation dose rate emanating from the patients with differentiated thyroid cancer undergoing radioiodine (I-131) therapy. *World J Nucl Med* 16:150–155; 2017. DOI:10.4103/1450-1147.203078.
- Demir M, Kabasakal L, Önsel Ç. Evaluation of external radiation exposure rate from radioiodine-treated hyperthyroid patients and radiation safety considerations. *Nucl Med Comm* 17:692–695; 1996. DOI:10.1080/0006231-199608000-00008.
- Demir M, Demir B, Sayman H, Sager S, Sabbir Ahmed A, Uslu I. Radiation protection for accompanying person and radiation workers in PET/CT. *Radiat Protect Dosim* 147:528–532; 2011. DOI:10.1093/rpd/ncq497.
- Dos Santos JAM, Antunes VCM, Da Silva Trindade Duarte LH. Radiation exposure of the members of the public from patients treated with 37 GBq and 185 GBq of ^{131}I —may we simply divide by 2? *Health Phys* 109:249–257; 2015. DOI:10.1097/HP0000000000000329.
- Dunn OJ, Clark VA. Basic statistics: a primer for the biomedical sciences. Hoboken: Wiley & Sons; 2009.
- European Commission. Radiation protection following iodine-131 therapy (exposures due to out-patients or discharged in-patients). Luxembourg: European Commission; Radiation Protection 97; 1998.
- Fayad E, Maia S, Zilnus A, Secchi V, Erra B, Perault C, Bakhsh A, Casset-Senon D, Santiago-Ribeiro M-J, Venel Y. Care continuity in post-scintigraphy period and radioactivity exposure of medical and technical staff. *Med Nucleaire* 39:380–385; 2015. DOI:10.1016/j.mednuc.2015.05.003.
- Gomes RQ, Carvalho JW, Oliveira MA, Abe R, Soares J Jr, Buchpiguel CA, Stabin MG, Guimaraes MICC. Evaluation of radiation doses from patients in ^{18}F FDG nuclear medicine procedures. In: IAEA Ed. Proceedings of IRPA 12 Conference; 2010.
- Gomez-Palacios M, Terrón JA, Domínguez P, Vera DR, Osuna RF. Radiation doses in the surroundings of patients undergoing nuclear medicine diagnostic studies. *Health Phys* 89:S27–S34; 2005. DOI:10.1097/01.hp.0000165873.12868.59.
- Greaves CD, Tindale WB. Dose rate measurements from radiopharmaceuticals: implications for nuclear medicine staff and for children with radioactive parents. *Nucl Med Comm* 20:179–188; 1999.
- Güneş BY, Erez Ö, Gündoğan C, Ergül N. The evaluation of external dose rate measurements of patients during and after F-18 FDG PET/CT imaging and appropriate discharge time from PET/CT department. *Istanbul Med J* 20:188–192; 2019. DOI:10.4274/imj.85698.
- Han EY, Lee C, McGuire L, Brown TLY, Bolch WE. Organ S values and effective doses for family members exposed to adult patients following I-131 treatment: a Monte Carlo simulation study. *Med Phys* 40:083901; 2013. DOI:10.1118/1.4812425.
- Han S, Jin S, Yoo SH, Lee HS, Lee SH, Jeon MJ, Ryu J-S. A practical individualized radiation precaution based on the dose rate at release time after inpatient ^{131}I ablation therapy. *PLoS ONE* 16:e0251627; 2021. DOI:10.1371/journal.pone.0251627.
- Hänscheid H, Lassmann M, Luster M, Thomas SR, Pacini F, Ceccarelli C, Ladenson PW, Wahl RL, Schlumberger M, Ricard M, Driedger A, Kloos RT, Sherman SI, Haugen BR, Carriere V, Corone C, Reiners C. Iodine biokinetics and dosimetry in radioiodine therapy of thyroid cancer: procedures and results of a prospective international controlled study of ablation after rhTSH or hormone withdrawal. *J Nucl Med* 47:648–654; 2006.
- Havlik E, Kurtaran A, Preitfellner J. Radiation exposure around patients after administration of Tc-99m-DPD or Tl-201-chloride. In: Proceedings of IRPA 9 Conference vol. 3. Seibersdorf: International Radiation Protection Association; 1996:550–552.
- International Atomic Energy Agency. Release of patients after radionuclide therapy. Vienna: IAEA; Safety Reports Series No. 63; 2009.
- International Commission on Radiation Units and Measurements. Operational quantities for external radiation exposure. Bethesda, MD: International Commission on Radiation Units and Measurements; ICRU Report 95; 2020.
- International Commission on Radiological Protection. Release of patients after radionuclide therapy with unsealed radionuclides. Oxford: Elsevier; ICRP Publication 94; Ann. ICRP 34(2); 2004.

- Javed M, Rahman SU, Tanveer I, Asghar G, Fatima S, Fahim M. Measurement of radiation doses to occupational workers in nuclear medicine. *Pakistan J Nucl Med* 7:16–19; 2017. DOI:10.24911/PJNMed.7.3.
- Kim HS, Cho JH, Shin SG, Dong KR, Chung WK, Chung JE. A study on quantitative analysis of exposure dose caused by patient depending on time and distance in nuclear medicine examination. *Radiat Effects Defects Solids* 168:80–87; 2013. DOI:10.1080/10420150.2012.670859.
- Konishi F, Abe K, Kusama T. Urinary excretion and external radiation dose from patients administered with radiopharmaceuticals. *Radiat Protect Dosim* 54:61–64; 1994. DOI:10.1093/oxfordjournals.rpd.a082317.
- Lamart S, Blanchardon E, Molokanov A, Kramer GH, Broggio D, Franck D. Study of the influence of radionuclide biokinetics on the efficiency of in vivo counting using Monte Carlo simulation. *Health Phys* 96:558–567; 2009. 10.1097/01.HP.0000342828.21935.e4.
- Lemoine J, Bourre JC, Giraud JY. Radiation doses in the surrounding of patients undergoing a nuclear medicine exam. *Radioprotect* 46:533–545; 2011. DOI:10.1051/radiopro/2011143.
- Liu B, Peng W, Huang R, Tian R, Zeng Y, Kuang A. Thyroid cancer: radiation safety precautions in ^{131}I therapy based on actual biokinetic measurements. *Radiol* 273:211–219; 2014. DOI:10.1148/radiol.14132234.
- Liu B, Tian R, Peng W, He Y, Huang R, Kuang A. Radiation safety precautions in ^{131}I therapy of Graves' disease based on actual biokinetic measurements. *J Clinical Endocrinol Metab* 100:2934–2941; 2015a. DOI:10.1210/jc.2015-1682.
- Liu Y-C, Lee K-W, Sheu R-J. Comparing dose rates near a radioactive patient evaluated using various source models: point, line, cylinder, and anthropomorphic phantoms. *Health Phys* 109:69–77; 2015b. DOI:10.1097/HP.0000000000000294.
- Markwardt CB. Non-linear least squares fitting in IDL with MPFIT. In: Bohlender D, Dowler P, Durand D, eds. *Proceedings of Astronomical Data Analysis Software and Systems XVIII*, Quebec, Canada, ASP Conference Series, Vol. 411. San Francisco: Astronomical Society of the Pacific; 251–254; 2009.
- Matheoud R, Reschini E, Canzi C, Voltini F, Gerundini P. Potential third-party radiation exposure from outpatients treated with ^{131}I for hyperthyroidism. *Med Phys* 31:3194–3200; 2004. DOI:10.1118/1.1809781.
- Mat Nawi N, Ahmad NS, Abdullah R, Zainon WMN, Abdul Razab MKA. Correlation of external dose rate with whole body clearance estimation in radioiodine therapy for rhTSH and THW patients. *J Radiat Res Appl Sci* 13:240–245; 2020. DOI:10.1080/16878507.2020.1727675.
- Morán V, Prieto E, García-García B, Barbés B, Ribelles MJ, Richter JA, Martí-Climent JM. Radiation dose produced by patients during radiopharmaceutical incorporation in nuclear medicine diagnostic procedures. *Revista Española de Medicina Nuclear e Imagen Molecular (English Edition)* 35:175–185; 2016. DOI:10.1016/j.remnie.2016.02.004.
- Mountford PJ, O'Doherty MJ, Forge NI, Jeffries A, Coakley AJ. Radiation dose rates from adult patients undergoing nuclear medicine investigations. *Nucl Med Comm* 12:767–777; 1991. DOI:10.1097/00006231-199109000-00003.
- Muhammad W, Faaruq S, Matiullah Hussain A, Khan AA. Release criteria from hospitals of ^{131}I thyrotoxicosis therapy patients in developing countries—case study. *Radiat Protect Dosim* 121:136–139; 2006. DOI:10.1093/rpd/ncl003.
- O'Doherty MJ, Kettle AG, Eustance CNP, Mountford PJ, Coakley AJ. Radiation dose rates from adult patients receiving ^{131}I therapy for thyrotoxicosis. *Nucl Med Comm* 14:160–168; 1993. DOI:10.1097/00006231-199303000-00003.
- Ohiduzzaman M, Khatun R, Reza S, Khan KA, Akter S, Uddin MF, Ahasan MM. Study of exposure rates from various nuclear medicine scan at INMAS, Dhaka. *Int J Advance Res Innovat Ideas Ed* 5:208–218; 2019.
- Pant G, Senthamizhchelvan S. Radiation exposure to staff in a PET/CT facility. *Indian J Nucl Med* 21:100–103; 2006.
- Quinn B, Holahan B, Aime J, Humm J, Germain JS, Dauer LT. Measured dose rate constant from oncology patients administered ^{18}F for positron emission tomography. *Med Phys* 39:6071–6079; 2012. DOI:10.1118/1.4749966.
- Rohatgi A. WebPlotDigitizer: version 4.5 [online]. 2020. Available at <https://automeris.io/WebPlotDigitizer/index.html>. Accessed 3 March 2021.
- Siegel JA, Marcus CS, Sparks RB. Calculating the absorbed dose from radioactive patients: the line-source versus point-source model. *J Nucl Med* 43:1241–1244; 2002.
- Sparks RB, Siegel JA, Wahl RL. The need for better methods to determine release criteria for patients administered radioactive material. *Health Phys* 75:385–388; 1998. DOI:10.1097/00004032-199810000-00004.
- Stenstad LV, Pedersen GA, Landmark AD, Brattheim B. Nuclear radiation dose to the surroundings from patients who are undergoing nuclear medicine examinations. *Radiography Open* 1:11–18; 2014. DOI:10.7577/radopen.1196.
- Sudbrock F, Boldt F, Kobe C, Hammes J, Eschner W, Schicha H. Radiation exposure in the environment of patients after application of radiopharmaceuticals. Part 2: therapeutic procedures. *NuklearMedizin* 48:17–25; 2009. DOI:10.3413/nukmed-0193.
- Sudbrock F, Uhrhan K, Rimpler A, Schicha H. Dose and dose rate measurements for radiation exposure scenarios in nuclear medicine. *Radiat Meas* 46:1303–1306; 2011. DOI:10.1016/j.radmeas.2011.06.074.
- Taprogge J, Carnegie-Peake L, Murray I, Gear J, Flux G. Adjustment of the iodine ICRP population pharmacokinetic model for the use in thyroid cancer patients after thyroidectomy. *J Radiolog Protect* 41:A3; 2021.
- Uhrhan K, Drzezga A, Sudbrock F. The patient as a radioactive source: an intercomparison of survey meters for measurements in nuclear medicine. *Radiat Protect Dosim* 162:101–104; 2014. DOI:10.1093/rpd/ncu238.
- US Nuclear Regulatory Commission. Title 10 Code of Federal Regulations Part 35: medical use of byproduct material. Washington, DC: US NRC; 2021.
- Willegaignon J, Guimarães MIC, Stabin MG, Sapienza MT, Malvestiti LF, Marone MMS, Sordi GMAA. Correction factors for more accurate estimates of exposure rates near radioactive patients: experimental, point, and line source models. *Health Phys* 93:678–688; 2007. DOI:10.1097/01.HP.0000275298.69543.5c.
- Wolberg J. Data analysis using the method of least squares. New York: Springer; 2006.
- Yi Y, Stabin MG, McKaskle MH, Shone MD, Johnson AB. Comparison of measured and calculated dose rates near nuclear medicine patients. *Health Phys* 105:187–191; 2013. DOI:10.1097/HP.0b013e318290cc0e.
- Zanzonico PB, Siegel JA, Germain JSt. A generalized algorithm for determining the time of release and the duration of post-release radiation precautions following radionuclide therapy. *Health Phys* 78:48–659; 2000. DOI:10.1097/00004032-200006000-00007.