CORRECTION FACTORS FOR MORE ACCURATE ESTIMATES OF EXPOSURE RATES NEAR RADIOACTIVE PATIENTS: EXPERIMENTAL, POINT, AND LINE SOURCE MODELS

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Abstract—Radioactive patients may expose others after radiopharmaceutical administrations, and evaluation of the absorbed dose or exposure rates close to patients is important in keeping radiation doses as low as reasonably achievable. Two theoretical exposure models, point source and line source models, are frequently used to calculate exposure or dose rates without the support of actual measurements. If measurements of exposure rates were performed near patients, an experimental exposure model could be implemented. When measurements of exposure rates are performed, these measurements are made inside therapy rooms or other confined places, in which case scattered radiation may significantly influence the measurements. In this study we measured exposure rates from radioactive patients without the influence of scattered radiation and determined correction factors for the theoretical exposure models. The exposure rates from a total of 110 radioactive patients were measured at 1.0 h after oral administration of Na$^{131}$I for thyroid therapy; the results ±1 SD at distances of 0.5, 1.0, 1.5, 2.0, 3.0, and 4.0 m in front of the patients were (29 ± 6), (9.9 ± 1.7), (4.6 ± 0.9), (2.7 ± 0.5), (1.31 ± 0.25) and (0.74 ± 0.12) × 10⁻¹⁸ C kg⁻¹ MBq⁻¹ h⁻¹, respectively. To obtain more accurate estimates of the actual exposure rates from patients using the theoretical exposure models, we found that correction factors should be applied; the functions CF$_{PM}$ = 1.19 + 32.8h⁻⁵ and CF$_{PS}$ = 0.022Ln(D) + 0.639 describe these correction factors for distances less than or equal to 1.0 m from the patients for experimental and line source exposure models, respectively. The function that describes the correction factors to the point source model is CF$_{PS}$ = 0.224Ln(D) + 0.638 at the same distances; applying these correction factors leads to a reduction from 56% to 1% in the difference between measured exposure rates and theoretical exposure rates calculated by the point source exposure model at a distance of 1.0 m from patients. The results given here provide more accuracy in evaluation of exposure rates and consequently absorbed doses near radioactive patients and allow for more effective radiological protection procedures during patient management. Health Phys. 93(6):678–688; 2007

Key words: Na$^{131}$I; medical radiation; dose assessment; correction factors

INTRODUCTION

Na$^{131}$I is widely used in the treatment of thyroid diseases; the treated patients represent sources of exposure to others for some period after the administration of therapeutic activity. Radioprotection recommendations are necessary for limiting radiation doses to others who come into close contact with these subjects. Normally these recommendations involve theoretical evaluation of the potential absorbed dose, routinely performed at 1.0 m from the patients (NCRP 1970; U.S. NRC 1997; Siegel et al. 2002a). Although many studies have discussed releasing patients from hospitals just after radiopharmaceutical administration and its influence on the quality of patients’ life (e.g., Siegel et al. 2002b; Rutar et al. 2001; Lubin 2002; ICRP 2004), it is still a common procedure to hospitalize patients for treatments that employ Na$^{131}$I activity greater than 1.11 GBq (30 mCi), as well as for other procedures that use large quantities of radiopharmaceuticals or permanent implants. Evaluation of the potential absorbed doses at distances other than 1.0 m would be helpful in protecting family members and could also be useful in dose reconstructions for hospital staff (Siegel et al. 2002a; Barrington et al. 1996; Culver and Dworkin 1991; Griffiths et al. 2000; Marcus and Siegel 2004).

Inpatient and outpatient radioprotection recommendations are usually based on exposure (or dose) rates measured at 1.0 m in front of the patients, with measurements frequently performed indoors. Nevertheless, outside of clinics and hospitals patients may be in more open
places, and the radiation doses to others may be overestimated by including the contributions from scattered radiation inside buildings. When not measured, the exposure rates used for dose evaluation are normally determined using one of two theoretical exposure models, point source and line source. These models simplify the calculations, but they generally overestimate exposure rates because they do not consider the attenuation and scattering of radiation by the patient's body and assume a uniform distribution of activity in the body. Some published models also neglect the biological removal of the radionuclide as a function of time (Siegel et al. 2002a; Sparks et al. 1998). Direct measurement is the best way to determine the exposure rates (or doses rates) (Rutar et al. 2001), but it is impractical to determine these rates as a function of distance for all patients in a hospital's daily routine. One solution is to use correction factors applied to results from theoretically calculated exposure rates to provide more accuracy in the evaluation of exposure rates from radioactive patients.

MATERIALS AND METHODS

A total of 129 patients were followed after Na\(^{131}\)I therapeutic procedures (19 cases of hyperthyroidism and 110 cases of differentiated thyroid cancer): 104 patients were females and 25 were males, with ages ranging from 18 to 88 y. All patients diagnosed with thyroid cancer were previously submitted to total or near-total thyroidectomy and interrupted thyroid hormone reposition for 4–6 wk and followed an iodine-poor diet before receiving Na\(^{131}\)I therapy to place the patients in a hypothyroid state and consequently to increase endogenous thyroid-stimulating hormone (TSH) levels (>30 mIU L\(^{-1}\)) and to stimulate thyroid radiiodine uptake. No exogenous recombinant human TSH (rhTSH) was administered to any patient. The patients diagnosed with hyperthyroidism were also submitted to a protocol for increasing radiiodine uptake. Clinical evaluation was routinely performed by a nuclear medicine physician before treatment and included evaluation of any associated illnesses that could influence the treatment, including any clinical records of renal insufficiency. The mean value ±1 SD (standard deviation) for the patients' weight was (72 ± 16) kg and for their height was (165 ± 9) cm. The Na\(^{131}\)I activities administered to all patients ranged from 0.74 GBq (20 mCi) to 16.6 GBq (450 mCi). An activity of 1.11 GBq (30 mCi) or less was administered to patients with hyperthyroidism, and for patients with thyroid cancer the administered activity was greater or equal than 3.7 GBq (100 mCi), increasing the amount according to therapeutic requirements.

Exposure rates from these radioactive patients were measured from 0.5 to 4.0 m (at intervals of 0.5 m) in front of the patients at 1.0 m over the floor. When radioiodine is administered orally as \(^{131}\)I in solution it is rapidly absorbed into the systemic circulation, and after 1.0 h almost all activity administered is distributed throughout the patients' bodies. All measurements were performed at about 1.0 h after Na\(^{131}\)I administration, when no urinary excretion had occurred, and were acquired inside the therapy rooms where administration occurred (the room dimensions were 2.6 × 3.6 m, 3.4 × 7.0 m, and 5.0 × 6.5 m). The patients were positioned along the axial center of the room to perform the measurements; the walls of the therapeutic rooms were resurfaced with dense concrete (about 3.0 cm, density \(\sim 4.0\) g cm\(^{-3}\)). Because of the arrangement of the therapeutic rooms the radiation scattered from materials inside the therapy room (such as the bed, chair, etc.) was considered negligible compared to the scattered radiation from the walls of the room.

Exposure rates were also measured for 5 experimental point sources of \(^{131}\)I, with activities of 3.7, 5.55, 7.4, 9.25, and 11.1 GBq (100, 150, 200, 250, and 300 mCi). These sources were confined in 6-mL glass bottles; scattered radiation from the bottle wall was considered negligible because the ratio between calculated exposure rates using a point source model and from an experimental point source of the same activity was close to 1.0. These \(^{131}\)I sources were provided by the IPEN—Instituto de Pesquisas Energéticas e Nucleares, Department of Radiopharmacy. Because of the dimensions of the therapeutic rooms, the measurements of exposure rates were made at 0.5 m to 2.5 m from the subjects for the two smaller therapeutic rooms and at 0.5 m to 4.0 m for the largest room. To measure the exposure rates, the radioactive sources and the gamma detector were both positioned at 1.0 m above the floor and in the same configuration used for patient measurements. Fig. 1 shows the schematic arrangement used for patient and experimental point source measurements.

A Geiger-Muller Model 190 detector (NS 2151, Victoreen Co., Elimpex—Medizintechnik, Spechtgasse 32, A-2340 Moedling, Austria), and a beta-gamma probe (Model 491–40, NS 2174, Elimpex—Medizintechnik, Spechtgasse 32, A-2340 Moedling, Austria) were used for the measurement of exposure rates. The detector was calibrated by the IPEN, Department of Radiation Metrology, using the methodology of the well known radiation field of a \(^{137}\)Cs source, calibrated with a standard ion chamber as a secondary standard (1 liter, Model PTW L50L, NS W32002-035—Physikalisch—Technische Werkstätten, PTW, Germany).

Theoretical exposure rates were calculated using point and line source exposure models. For the point
source, the exposure rates were calculated using the following equation:

\[ \hat{X} = (\Gamma A) \frac{d}{2} \left[ \frac{C}{kg^{-1} h^{-1}} \right] , \]  

(1)

where \( \Gamma \) is the specific gamma ray constant for \(^{131}\)I at 1.0 m \((1.53 \times 10^{-3} \frac{C}{kg^{-1} m^3} \text{ MBq}^{-1} \text{ h}^{-1} [22 \times 10^{-3} \text{ R m}^2 \text{ mCi}^{-1} \text{ h}^{-1}] \) (ICRU 1993, 1998; Siegel et al. 2002b; Cherry et al. 2003), \( A \) is the activity (in MBq), and \( d \) is the distance from the source (in m). For the line source model, the methodology used in the calculation is shown in Fig. 2 and is given as:

\[ \hat{X} = (\Gamma q a^{-1} h^{-1}) \theta \left[ \frac{C}{kg^{-1} h^{-1}} \right] . \]  

(2)

Here \( \Gamma \) is the specific gamma ray constant for \(^{131}\)I, \( q \) is the activity distributed in the source (in MBq), \( a \) is the source length (in m), \( h \) is the distance from the source (in m), and \( \theta \) is the angle in radians (Hine and Brownell 1956).

**RESULTS**

The mean value \( \pm 1 \text{ SD} \) for the exposure rates from a total of 110 radioactive patients (patients with differentiated thyroid cancer) that were measured inside of the large 3.4 \( \times \) 7.0 m therapy room is given in Table 1. The table also shows exposure rates calculated using the point source and line source models (eqns 1 and 2) and the ratios between measured patient exposure rates and those calculated using the models. All exposure rates are presented as a function of distance from the radioactive sources and for a unit activity of 1 MBq. Fig. 3 presents the dispersion of all exposure rates from patients indicated in Table 1 at distances of 1.0 m and 2.0 m. Also shown is a function that gives the expected exposure rate given by the point source model.

When measurements of exposure rates from radioactive sources are performed inside of buildings, scattered radiation may influence the measurements. The amount of scattered radiation depends on the geometry of the source and on the building geometry. One method of evaluating the scattered radiation from building geometry is by comparing modeled exposure rates and measured exposure rates for the same source activity. Table 2 presents the measured exposure rates from experimental point sources when the sources are in different sized therapy rooms and the ratios between these exposure rates and those calculated using a point source model of the same activity.

Fig. 4 shows the decrease in measured exposure rates from patients (Table 1) and from point sources as a function of distance, from measurements performed inside of the 3.4 \( \times \) 7.0 m therapy room. The figure also
Table 1. Exposure rates measured from patients and calculated using point and line source models ($10^{-10}$ C kg$^{-1}$ MBq$^{-1}$ h$^{-1}$) and ratios between measured and calculated exposure rates.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure rate from patients</td>
<td>28 ± 6</td>
<td>11.2 ± 1.9</td>
<td>6.2 ± 1.2</td>
<td>3.9 ± 0.7</td>
<td>2.8 ± 0.5</td>
<td>2.1 ± 0.4</td>
<td>1.6 ± 0.3</td>
<td>1.33 ± 0.22</td>
</tr>
<tr>
<td>Point source model</td>
<td>61.9 ± 0.9</td>
<td>15.48 ± 0.23</td>
<td>6.88 ± 0.10</td>
<td>3.87 ± 0.06</td>
<td>2.48 ± 0.04</td>
<td>1.72 ± 0.03</td>
<td>1.26 ± 0.019</td>
<td>0.97 ± 0.015</td>
</tr>
<tr>
<td>Ratio, patient to PS model</td>
<td>0.45 ± 0.09</td>
<td>0.72 ± 0.12</td>
<td>0.90 ± 0.17</td>
<td>1.00 ± 0.18</td>
<td>1.13 ± 0.20</td>
<td>1.22 ± 0.23</td>
<td>1.27 ± 0.19</td>
<td>1.37 ± 0.23</td>
</tr>
<tr>
<td>Line source model</td>
<td>46.2 ± 2.6</td>
<td>15.5 ± 0.9</td>
<td>7.6 ± 0.4</td>
<td>4.41 ± 0.25</td>
<td>2.87 ± 0.16</td>
<td>2.02 ± 0.11</td>
<td>1.49 ± 0.08</td>
<td>1.14 ± 0.06</td>
</tr>
<tr>
<td>Ratio, patient to LS model</td>
<td>0.61 ± 0.14</td>
<td>0.72 ± 0.13</td>
<td>0.82 ± 0.16</td>
<td>0.88 ± 0.17</td>
<td>0.98 ± 0.18</td>
<td>1.04 ± 0.21</td>
<td>1.07 ± 0.21</td>
<td>1.17 ± 0.20</td>
</tr>
</tbody>
</table>

$^a 1.0 \times 10^{-10}$ C kg$^{-1}$ MBq$^{-1}$ h$^{-1} = 14.34 \times 10^{-8}$ R mCi$^{-1}$ h$^{-1}$.

shows exposure rates calculated using the point source and line source models. Since the mean value ± 1 SD for the patients’ height was 165 ± 9 cm, and the radioiodine is assumed to be rapidly dispersed throughout the patients’ body after administration, the length of the line source used in the calculation was assumed to be 165 cm.

The ratios in Table 2 allow evaluation of the radiation scattered by the building and the patient; the knowledge of this scattered radiation allows the appropriate adjustment of the exposure rates from patients. The scattered radiation was estimated knowing the difference between measured exposure rates from experimental point sources and calculated exposure rates from point sources of the same activity (eqn 2). The difference between measured and calculated exposure rates was associated with the scattered radiation and its influence on the measurement. Considering that the same scattering occurs for radioactive patients inside of buildings, the measured exposure rates from patients were adjusted using the ratios between calculated exposure rates and measured exposure rates from the point sources.

Eqn (3) gives the methodology used to adjust the exposure rates from patients from measurements performed inside of buildings:

$$\hat{X}(d)_{\text{Patient-adjusted}} = \frac{\hat{X}(d)_{\text{Patient-measured}}}{\hat{X}(d)_{\text{PS-theoretical}}},$$  

(3)

where

$$\hat{X}(d)_{\text{Patient-adjusted}} = \text{adjusted exposure rate from patients at distance } d;$$  
$$\hat{X}(d)_{\text{Patient-measured}} = \text{measured exposure rate from patients};$$  
$$\hat{X}(d)_{\text{PS-theoretical}} = \text{calculated exposure rate from the point source model; and}$$

![Fig. 3. Exposure rates measured at 1.0 m and 2.0 m in front of the patients' body surface.](image-url)
### Table 2. Measured point source exposure rates ($10^{-10}$ C kg$^{-1}$ MBq$^{-1}$ h$^{-1}$) in different sized therapy rooms and ratios between measured and point source model exposure rates.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure rate</td>
<td>3.4 × 7.0 m$^3$</td>
<td>60.7 ± 1.6</td>
<td>17.6 ± 0.6</td>
<td>9.15 ± 0.24</td>
<td>5.50 ± 0.17</td>
<td>3.72 ± 0.11</td>
<td>2.75 ± 0.09</td>
<td>2.17 ± 0.07</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.98 ± 0.03</td>
<td>1.14 ± 0.04</td>
<td>1.33 ± 0.04</td>
<td>1.42 ± 0.05</td>
<td>1.50 ± 0.05</td>
<td>1.60 ± 0.06</td>
<td>1.72 ± 0.07</td>
<td>1.77 ± 0.07</td>
</tr>
<tr>
<td>Exposure rate</td>
<td>5.0 × 6.5 m</td>
<td>54 ± 4</td>
<td>15.8 ± 1.1</td>
<td>7.8 ± 0.4</td>
<td>4.87 ± 0.26</td>
<td>3.72 ± 0.39</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.88 ± 0.06</td>
<td>1.02 ± 0.07</td>
<td>1.14 ± 0.06</td>
<td>1.26 ± 0.07</td>
<td>1.50 ± 0.16</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Exposure rate</td>
<td>2.6 × 3.6 m</td>
<td>51.4 ± 1.7</td>
<td>16.9 ± 1.5</td>
<td>8.5 ± 0.5</td>
<td>5.37 ± 0.17</td>
<td>4.22 ± 0.26</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.83 ± 0.03</td>
<td>1.09 ± 0.10</td>
<td>1.24 ± 0.07</td>
<td>1.39 ± 0.05</td>
<td>1.70 ± 0.11</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

*1.0 × 10$^{-10}$ C kg$^{-1}$ MBq$^{-1}$ h$^{-1}$ = 14.34 × 10$^{-6}$ R mCi$^{-1}$ h$^{-1}$.

* Room dimensions.

\[ \hat{\lambda}(d)_{\text{PS,measured}} = \text{measured exposure rate from a point source.} \]

The measured exposure rate from the point source considered in eqn (3) is the mean value of exposure rates from experimental point sources measured at the same distance \(d\) from the sources that were measured inside of the 3.4 × 7.0 m therapy room; the mean value of the exposure rates from the experimental point source is presented in Table 2 for different sized therapy rooms.

The adjusted exposure rates from patients per MBq administered at distances of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 m from the subjects were (29 ± 6), (9.9 ± 1.7), (4.6 ± 0.9), (2.7 ± 0.5), (1.9 ± 0.3), (1.31 ± 0.25), (0.93 ± 0.17), and (0.74 ± 0.12) × $10^{-10}$ C kg$^{-1}$ MBq$^{-1}$ h$^{-1}$ [1.0 × $10^{-10}$ C kg$^{-1}$ MBq$^{-1}$ h$^{-1}$ = 14.34 × $10^{-6}$ R mCi$^{-1}$ h$^{-1}$], respectively.

Accounting for differences between the adjusted exposure rates from patients and exposure rates measured from point sources and calculated using point and line source models, equations were developed to describe the needed correction factors (\(CF_{EM}\), \(CF_{PS}\), and \(CF_{LS}\)). The mean value of the exposure rates measured at 0.10 m from the patients, including data provided by Barrington et al. (1996), was used in this study to help determine the correction factors equations for distances less than 1.0 m from the patients. These correction factors allow adjustment of the exposure rates calculated using theoretical exposure models, based on the actual patient exposure rate measurements.

The experimental model correction factor \(CF_{EM}\) was developed based on the ratios between the measured exposure rates at other distances from the patients and the exposure rates measured at 1.0 m from patients. All measured exposure rates from patients were adjusted by eqn (3) to determine the ratios. The functions that describe the correction factors for the experimental model are

\[
CF_{EM} = 1.19 + 32.80e^{-5.92D}
\]

![Fig. 4. Decrease in the measured and calculated exposure rates as function of distance from radioactive sources.](image-url)
at distances less or equal than 1.0 m \((R^2 = 0.999)\), and

\[ CF_{EM} = 0.088 + 4.76e^{-1.66D} \]  

(5)

for distances greater than 1.0 m \((R^2 = 0.997)\), where \(D\) is the distance from the patient, in m.

The point source model correction factor \(CF_{PS}\) is based on the ratios between adjusted exposure rates from patients and exposure rates calculated using the point source model in eqn (1). The point source model correction factor is described by the equations

\[ CF_{PS} = 0.224Ln(D) + 0.638 \]  

(6)

for distances less than or equal than 1.0 m \((R^2 = 0.999)\), and

\[ CF_{PS} = -0.020D^2 + 0.14D + 0.52 \]  

(7)

for distances greater than 1.0 m \((R^2 = 0.904)\), where \(D\) is distance from the patient, in m. Fig. 5a–d shows the fitted functions that give the ratios between adjusted exposure rates from patients and theoretical exposure rates as given in eqns (4), (5), (6), and (7). The same methodology was made for the line source model to provide the correction factor \(CF_{LS}\) (eqns 8 and 9).

The line source model correction factor \(CF_{LS}\) is based on the ratios between adjusted exposure rates from patients and exposure rates calculated using the line source model in eqn (2). The line source model correction factor is described by the equations

\[ CF_{LS} = -0.022Ln(D) + 0.639 \]  

(8)

for distances less than or equal than 1.0 m \((R^2 = 0.989)\), and

\[ CF_{LS} = 0.634 \]  

(9)

for distances greater than 1.0 m, where \(D\) is distance from the patient, in m.

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**Fig. 5.** (a) Fitted function to describe the ratios between adjusted exposure rates at distances less than or equal to 1.0 m from patients and adjusted exposure rate at 1.0 m from patients; (b) Fitted function to describe the ratios between adjusted exposure rates for distances greater than 1.0 m from patients and adjusted exposure rate at 1.0 m from patients; (c) Fitted function to describe the ratios between adjusted exposure rates from patients and calculated exposure rates for distances less than or equal to 1.0 m using the point source model (eqn 1); (d) Fitted function to describe the ratios between adjusted exposure rates from patients and calculated exposure rates for distances greater than 1.0 m using the point source model (eqn 1).
DISCUSSION

A number of guidelines exist regarding the management of patients after radiopharmaceutical therapy administrations (NCRP 1970; U.S. NRC 1997). In the hospital daily routine there are basically two widely implemented methods for releasing patients after radiopharmaceutical administrations: the first is to release patients based on the retained activity in their bodies, and the second is to release them based on measured or calculated exposure rates. Other possibilities may also be implemented, considering the social life and economic factors of each patient (ICRP 1996; ICRP 2004). Values of instantaneous exposure rates and activity retained do not represent adequate methodologies per se because they are based on temporal measures and do not take into account the reduction of activity and exposure rates as function of elapsed time after radiiodine administration. The best methodology would be to evaluate the potential for exposing others, using an absorbed dose evaluation for each particular patient (U.S. NRC 1997).

This study evaluated measurement methodologies and the possible influence of scattered radiation when patient measurements are performed indoors. Exposure rates from patients were determined without contribution from scattered radiation and, considering the differences between measured exposure rates from patients and exposure rates calculated using point and line source exposure models, correction factors were developed to adjust the theoretical exposure rates according to the actual exposure rates from the patients. Fig. 3 shows that at a distance of 2.0 m, some experimental exposure rates are greater than predicted using the point source model; these differences are likely due to the contribution of scattered radiation to measurements performed inside therapy rooms. Fig. 4 shows the decrease in the exposure rates as a function of distance for the patient exposure rates and model calculations presented in Table 1 and from the measured point source exposure rates in the 3.4 × 7.0 m therapeutic room in Table 2. In this figure, it is observed that the line corresponding to the point source model exposure rates crosses the measured patient exposure rates at about 2.0 m. The point source measurements acquired at 2.0 m inside of the therapy room were in good agreement with the predictions from the point source model (eqn 1). The figure shows the possible overestimation of exposure rates using theoretical exposure models, especially for distances less than 1.0 m from the patients.

Previous studies made by our group (Willegaignon et al. 2006a and b) showed that almost all 131I activity administered to patients for the treatment of thyroid cancer is quickly dispersed in the blood, that excretion of radiiodine by the patient’s body occurs mostly during the first five days after the administration, and that only a small amount of activity is retained by the thyroid remnant tissue in thyroidectomized patients. For this reason, the line source exposure model better represents the exposure rates from patients than the point source model. Although we have not studied iodine excretion from patients with intact thyroids (patients with hyper-thyroidism), it is known that the thyroid has the highest iodine uptake 24 h or more after iodine administration; thus, the line source exposure model also better represents the exposure rates from these patients before this period. After this time it is possible that the point source model represents the best alternative in the evaluation of the exposure rates from these patients, because a great amount of 131I activity is retained by the thyroid gland and the distance of exposure rate measurement is always greater than the dimensions of this gland.

The ratios of exposure rates from experimental point source measurements inside of therapy rooms and calculated values from the point source model are given in Table 2; the ratios between the values increase with distance from the sources and with proximity to the wall; this finding was expected considering that the scattered radiation increases in these points in accordance with the size of the room. As was expected for central points inside the rooms, the measurements are not strongly influenced by the scattered radiation. No significant difference was found in the measured exposure rates at the same distance of measurement from the radioactive source for all therapeutic rooms (the exposure rates become more similar with the distance from the sources), indicating that the scattered radiation did not change much with room dimensions. This allows establishment of a mean value for the ratios between the measured point source exposure rates and exposure rates calculated using the point source model of the same activity; the mean values are 1.36 ± 0.08 at 1.0 m and 1.00 ± 0.18 at 2.0 m of distance from the radioactive sources. This finding is compatible with other findings by our group, which evaluated methods for determining the total amount of 131I activity inside of the patient’s body (Willegaignon et al. 2006c).

Comparing the exposure rates from point source measurements, point source model calculations, and the exposure rates from patients (Fig. 4) it is possible to determine the contributions of scattered radiation and attenuation of radiation by the patients’ bodies, and to appropriately adjust the exposure rates from the patients. Furthermore, ratios of the values permit determination of
correction factors for exposure rates calculated by theoretical models. On average, the experimental exposure rates from patients were 0.56 times (56% of) the value calculated by a point source model at 1.0 m. For the line source model, the percentage depends on the source length, as shown by other authors (Siegel et al. 2002a and b; Sparks et al. 1998).

The adjusted exposure rates from radioactive patients (exposure rates without the influence of the scattered radiation from building materials) at distances of 1.0 and 2.0 m are \((9.9 \pm 1.7) \times 10^{-10} \text{ C kg}^{-1} \text{ MBq}^{-1} \text{ h}^{-1}\) [142 \(\pm\) 24 \(\times\) 10\(^{-6}\) R mCi\(^{-1}\) h\(^{-1}\)] and \((2.7 \pm 0.5) \times 10^{-10} \text{ C kg}^{-1} \text{ MBq}^{-1} \text{ h}^{-1}\) [39 \(\pm\) 7 \(\times\) 10\(^{-6}\) R mCi\(^{-1}\) h\(^{-1}\)], respectively. Sparks et al. (1998) found a value of 9.04 \(\times\) 10\(^{-10}\) C kg\(^{-1}\) MBq\(^{-1}\) h\(^{-1}\) [130 \(\times\) 10\(^{-6}\) R mCi\(^{-1}\) h\(^{-1}\)] at 1.0 m using a mathematical model; this value is consistent with the values determined by this study. The difference between measured exposure rates inside therapeutic rooms and the exposure rates without the interference of scattered radiation demonstrates that the absorbed doses received in places where the radiation scattered is not present or may be neglected may be underestimated (our data suggest by about 13% at 1.0 m and 44% at 2.0 m) if based on measurements made in the presence of significant scattered radiation.

The correction factors \(CF_{PS}\) and \(CF_{LS}\) permit adjustment of exposure rates calculated using point and line source models, providing estimates more consistent with actual exposure rates from patients. The correction factor \(CF_{EM}\) provides the capability to determine the exposure rates at any distance from patients based on the measured exposure rates at 1.0 m from patients. Eqns (10) and (11) give the methodology for calculating exposure rates using the derived correction factors. When patient exposure rates cannot be measured directly they are evaluated using the exposure models, especially the point source and line source models. As shown in Fig. 4, these models overestimate the exposure rates near patients. The application of the correction factors \((CF_{EM}, CF_{PS}, \text{ and } CF_{LS})\) to exposure rates calculated using the exposure models provides for more accurate exposure rate estimates. To calculate exposures rates at any distance from radioactive patients using correction factors is simple and easily implemented. For example, if the exposure rate at 1.0 m from patient is known, the exposure rate at other distances can be determined by multiplying the exposure rate by the correction factor \(CF_{EM}\):

\[
\hat{X}(d)_{\text{adjusted}} = \hat{X}(1.0)_{\text{measured}} \times CF_{EM}(d) \quad (10)
\]

If the exposure rate from patients is not known but determined by a theoretical exposure model, the approach is:

\[
\hat{X}(d)_{\text{adjusted}} = \hat{X}(d)_{\text{theoretical}} \times CF_{PS} \text{ or } CF_{LS}(d),
\]

where

- \(\hat{X}(d)_{\text{adjusted}}\) = adjusted exposure rate at distance \(d\);
- \(\hat{X}(d)_{\text{theoretical}}\) = calculated exposure rate from the point or line source model; and
- \(CF_{PS} \text{ or } CF_{LS}(d)\) = appropriate line source or point source correction factor.

Our data further suggest that an uncertainty of 18% should be applied to the exposure rates estimated using the correction factors. When the experimental values of the exposure rate at 1.0 m from patient are not available, the value of \((11.2 \pm 1.9) \times 10^{-10} \text{ C kg}^{-1} \text{ MBq}^{-1} \text{ h}^{-1}\) [161 \(\pm\) 27 \(\times\) 10\(^{-6}\) R mCi\(^{-1}\) h\(^{-1}\)] may be used when patients are inside buildings and \((9.9 \pm 1.7) \times 10^{-10} \text{ C kg}^{-1} \text{ MBq}^{-1} \text{ h}^{-1}\) [142 \(\pm\) 24 \(\times\) 10\(^{-6}\) R mCi\(^{-1}\) h\(^{-1}\)] may be used if scattering is assumed to be negligible.

To verify the correction factor method in reducing errors in the evaluation of exposure rates from radioactive patients using theoretical exposure models, the method was applied to the patients (P1, P2, and P3), and Table 3 presents exposure rates measured for these patients and the associated exposure rates calculated using point and line source models. The length of the line source was the patient’s actual height. Since the exposure rates from these patients were measured inside of the 3.4 \(\times\) 7.0 m therapeutic room, all exposure rates from these patients were adjusted using eqn (3) to compare the expected and observed exposure rates.

Fig. 6a–d presents the adjusted exposure rates from patients P1 and P3, the exposure rates calculated using the corrected experimental model, and the line and point source models both with and without correction. The figure shows the overestimation of exposure rates from theoretical exposure models without correction, especially from the point source model and at closer distances from the patients’ body surface (distances less than 1.0 m). Table 4 shows the deviation (in percentage) between measured exposure rates from patient P1 and exposure rates calculated using line and point source models with and without correction.

The data in Table 3 show that the corrected experimental exposure model, on average, results in the best agreement with the adjusted exposure rates from patients. Overall, the deviations from adjusted exposure rates from patients and calculated exposure rates corrected by \(CF_{EM}\), \(CF_{PS}\), and \(CF_{LS}\) were about 10.1%, 13.1%, and 13.5% for the experimental model, point source, and line source models, respectively. Yet, applying the correction factor \(CF_{PS}\) leads to a reduction from 56% to 1% in the difference between actual exposure rates and exposure.
Table 3. Adjusted exposure rates from three patients (P1, P2 and P3) and estimated exposure rates using the corrected experimental, point source, and line source models.

<table>
<thead>
<tr>
<th>Patient’s identification</th>
<th>Activity (GBq)</th>
<th>Exposure rate ($\times 10^{-3}$ C kg$^{-1}$ h$^{-1}$)</th>
<th>0.17$^a$</th>
<th>0.25</th>
<th>0.50</th>
<th>0.75</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Adjusted exposure rates</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>P1 (159 cm, 65 kg)</td>
<td>5.50</td>
<td>522 ± 26</td>
<td>346 ± 20</td>
<td>172 ± 12</td>
<td>89 ± 6</td>
<td>56 ± 3</td>
<td>26.0 ± 2.2</td>
<td>14.9 ± 0.6</td>
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<tr>
<td></td>
<td></td>
<td>Theoretical exposure rates</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>699 ± 126</td>
<td>459 ± 83</td>
<td>153 ± 28</td>
<td>84 ± 15</td>
<td>56 ± 3</td>
<td>26 ± 5</td>
<td>14 ± 3</td>
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<tr>
<td></td>
<td></td>
<td>710 ± 128</td>
<td>328 ± 59</td>
<td>164 ± 30</td>
<td>87 ± 16</td>
<td>54 ± 10</td>
<td>26 ± 5</td>
<td>15 ± 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>731 ± 132</td>
<td>456 ± 82</td>
<td>178 ± 32</td>
<td>94 ± 17</td>
<td>58 ± 10</td>
<td>28 ± 5</td>
<td>16 ± 3</td>
<td></td>
</tr>
<tr>
<td>P2 (167 cm, 66 kg)</td>
<td>5.50</td>
<td>951 ± 50</td>
<td>591 ± 31</td>
<td>247 ± 13</td>
<td>112 ± 6</td>
<td>66 ± 4</td>
<td>27.0 ± 2.3</td>
<td>15.6 ± 0.7</td>
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<tr>
<td></td>
<td></td>
<td>Theoretical exposure rates</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>857 ± 154</td>
<td>563 ± 101</td>
<td>188 ± 34</td>
<td>103 ± 19</td>
<td>66 ± 4</td>
<td>31 ± 6</td>
<td>17 ± 3</td>
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<tr>
<td></td>
<td></td>
<td>710 ± 128</td>
<td>328 ± 59</td>
<td>164 ± 30</td>
<td>87 ± 16</td>
<td>54 ± 10</td>
<td>26 ± 5</td>
<td>15 ± 3</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>701 ± 126</td>
<td>439 ± 79</td>
<td>173 ± 31</td>
<td>93 ± 17</td>
<td>57 ± 10</td>
<td>28 ± 5</td>
<td>16 ± 3</td>
<td></td>
</tr>
<tr>
<td>P3 (168 cm, 50 kg)</td>
<td>9.17</td>
<td>1008 ± 55</td>
<td>828 ± 50</td>
<td>337 ± 18</td>
<td>165 ± 10</td>
<td>102 ± 6</td>
<td>44.2 ± 2.2</td>
<td>24.7 ± 2.8</td>
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<tr>
<td></td>
<td></td>
<td>Theoretical exposure rates</td>
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<tr>
<td></td>
<td></td>
<td>1292 ± 233</td>
<td>848 ± 153</td>
<td>283 ± 51</td>
<td>155 ± 28</td>
<td>102 ± 6</td>
<td>47 ± 8</td>
<td>25 ± 4</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>1184 ± 213</td>
<td>743 ± 134</td>
<td>274 ± 49</td>
<td>145 ± 26</td>
<td>91 ± 16</td>
<td>43 ± 8</td>
<td>26 ± 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1099 ± 198</td>
<td>690 ± 124</td>
<td>272 ± 49</td>
<td>146 ± 26</td>
<td>90 ± 16</td>
<td>43 ± 8</td>
<td>25 ± 5</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ $2.58 \times 10^{-3}$ C kg$^{-1}$ h$^{-1} = 1.0 \times 10^{-3}$ R h$^{-1}$.

$^b$ Distance from patients (in m).

Rates calculated using the point source model at 1.0 m from patients. Thus, for practical purposes, it is preferable to use the corrected experimental exposure model or point source model rather than other methods for evaluating the exposure rates from patients. The mean value for exposure rates from patients at 1.0 m provided by this study could be useful for evaluating the exposure rates using the experimental exposure model when it is not possible to perform measurements with patients.

There were difficulties in establishing a unique function for describing the exposure rates from radioactive patients at all distances; one function was needed for describing the correction factor at a distance less than or equal to 1.0 m and another for distances greater than 1.0 m. At distances less than 1.0 m from the patients, the exposure rates may be very different for patients with similar body characteristics. This is seen in the adjusted exposure rates from patients P1 and P2 (Table 3), who received the same therapeutic activity and had similar body characteristics, but had very different exposure rates—about 82%, 71%, and 44% difference in the exposure rates at 0.17, 0.25, and 0.5 m, respectively. The metabolism of each patient influences the observed exposure rates, and this influence is most evident at distances close to the patients.

Table 4 shows the differences (in percentage) between adjusted exposure rates from patient P1 and exposure rates calculated using point and line source models with and without correction factors. Fig. 6a–d is based on Tables 3 and 4 and shows the reduction in the errors between exposure rates. According to the data for P1 in Table 4, the deviations between actual exposure rates and theoretical exposure rates were greatly reduced after the correction factors were applied. Similar results would be expected for other patients because the correction factors are based on measurements performed at 0.10 m to 4.0 m distances for a large number of radioactive patients and several different therapeutic activity levels.

In addition to the general difficulty in deriving a single method for estimating exposure rates from all patients, it was observed that the radiation fields near
patients are not uniform and do not increase with the inverse square law at closer distances; measurements as well may be influenced by the scattered radiation when they are performed indoors. Nevertheless, the exposure rates shown here represent mean values for a large number of patients and activities studied, and, despite the difficulties in applying them to all patients and distances, it was shown to be a viable method for reducing errors when using point and line source model exposure rates estimates. The method can allow radioprotection services to establish more effective radiological protection procedures during patient management.

Table 4. Deviation between adjusted exposure rates from patient P1 and calculated exposure rates from point and line source models with and without correction factors.

<table>
<thead>
<tr>
<th>Distance from patient (m)</th>
<th>0.17</th>
<th>0.25</th>
<th>0.50</th>
<th>0.75</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted exposure rates from P1 ( (\times 10^{-3} \text{ C kg}^{-1} \text{h}^{-1}) )</td>
<td>522 ± 26</td>
<td>346 ± 20</td>
<td>172 ± 12</td>
<td>89 ± 6</td>
<td>56 ± 3</td>
<td>26.0 ± 2.2</td>
<td>14.9 ± 0.6</td>
</tr>
<tr>
<td>Deviation between exposure rates (%)</td>
<td>464</td>
<td>294</td>
<td>98</td>
<td>70</td>
<td>52</td>
<td>46</td>
<td>43</td>
</tr>
<tr>
<td>Point source model (without correction)</td>
<td>36</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Line source model (without correction)</td>
<td>106</td>
<td>97</td>
<td>58</td>
<td>64</td>
<td>62</td>
<td>68</td>
<td>71</td>
</tr>
<tr>
<td>Point source model (with correction)</td>
<td>40</td>
<td>32</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

\( 1.0 \times 10^{-10} \text{ C kg}^{-1} \text{MBq}^{-1} \text{h}^{-1} = 1.43 \times 10^{-4} \text{ R mCi}^{-1} \text{h}^{-1} \).
CONCLUSION

Results from this study indicate that correction factors should be applied to point and line source model calculations to provide greater accuracy in estimating exposure rates and doses for patients administered therapy levels of radiopharmaceuticals. Determining the exposure rates near radioactive patients is important to maintain the radiation doses to as low as reasonably achievable “ALARA” levels and to design an adequate program for radiological protection in the management of these patients. The methodology shown here can be easily implemented and may be useful in the routine management of such patients.

Acknowledgments—The authors are grateful for the technical support provided by G.B. Courn Filho in preparing this article.

REFERENCES


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.


Willegaegn J, Stabin MG, Guimarães MIC, Malvestiti LF, Sapienza MT, Marone M, Sordi GMAA. Evaluation of the potential absorbed doses from patients based on the whole-body 131I clearance in thyroid cancer therapy. Health Phys 91:123–127; 2006b.