Note

A practical guideline for the release of patients treated by I-131 based on Monte Carlo dose calculations for family members

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Abstract

We recently published effective doses per time-integrated activity (mSv MBq\(^{-1}\) s\(^{-1}\)) for paediatric and adult family members exposed to an adult patient released from hospital following I-131 therapy. In the present study, we intend to provide medical physicists with a methodology to estimate family member effective dose in daily clinical practice because the duration of post-radiation precautions for the patient–family member exposure scenario has not been explicitly delineated based on the effective dose. Four different exposure scenarios are considered in this study including (1) a patient and a family member standing face to face, (2) a patient and a family member lying side by side, (3) an adult female patient holding a newborn child to her chest and (4) a one-year-old child standing on the lap of an adult female patient following her I-131 therapy. The results of this study suggest that an adult female hyperthyroidism (HT) patient who was administered with 740 MBq should keep a distance of 100 cm from a 15-year-old child for six days and the same distance from other adults for seven days. The HT female patient should avoid holding a newborn against her chest for at least 16 days following hospital discharge, and a female patient treated with 5550 MBq for differentiated thyroid...
cancer should not hold her newborn child for at least 15 days following hospital discharge. This study also gives dose coefficients allowing one to predict age-specific effective doses to family members given the measured dose rate (mSv h\(^{-1}\)) of the patient. In conclusion, effective dose-based patient release criteria with a modified NRC two-component model provide a site medical physicist with less restrictive and age-specific radiation precaution guidance as they fully consider a patient’s iodine biokinetics and photon attenuation within both the patient and the exposed family members.

Keywords: guideline, I-131, Monte Carlo

(Some figures may appear in colour only in the online journal)

1. Introduction

The United States Nuclear Regulatory Commission (USNRC) regulates the release of patients who have been administered radioactive materials with criteria based on the estimated total effective dose equivalent (TEDE) to any individuals exposed to the released patient to not exceed 5 mSv. Although three options to meet the criteria are given, administered activity, measured dose rate and patient-specific dose calculations, all options are based on the exposure rate constant defined as an exposure between a point source and a point target in air to represent the patient–family member exposure scenario.

The authors recently published organ S values (mGy MBq\(^{-1}\) s\(^{-1}\)) and effective doses per time-integrated activity (mSv MBq\(^{-1}\) s\(^{-1}\)) for both paediatric and adult family members exposed to an adult male or female patient treated with I-131 at various distances (Han et al 2013a, 2013b). A series of hybrid computational phantoms coupled with the Monte Carlo transport technique were adopted to simulate the realistic anatomy of both the patient and the family member. The authors found that the values of organ and effective doses to exposed family members were mainly dictated by the patient’s disease type (I-131 source distribution in the patient), the age and/or height of the family members and the distance/posture between the patient and family members. A site physicist in a nuclear medicine department should consider patient–family member specific dose estimates and also age-specific post-radiation precaution instructions.

Most nuclear medicine departments in the USA comply with the NRC recommendation on the patient release criteria using a measured dose rate or a patient-specific dose calculation. Instruction must be given to the patient and family members if the administered or retained activity at the time of patient release is higher than 0.24 GBq (7 mCi) or the measured dose rate is higher than 0.02 mSv h\(^{-1}\). However, no guideline to estimate the duration of post-radiation precautions is explicitly provided by NRC. Zanzonico et al (2000) reported a measured dose rate-based algorithm to determine the time of patient release and lengths of time for a patient not holding a child or not sleeping with a partner after radiiodine therapy. They used a distance of 0.3 m for the child held by the patient and 1 mSv as the maximum permissible effective dose equivalent (MPD) to both exposed children and pregnant women. Their work was also included in the national council on radiological protection (NCRP) report no. 155 (NCRP 2006). However, the results were not explicitly estimated based on effective dose, which is calculated through a simulation of two anthropomorphic computational phantoms coupled with Monte Carlo transport to simulate a realistic exposure scenario.
The purpose of this study was to provide a site physicist with practical guidelines for the release of radioiodine patients. We incorporated the effective doses per time-integrated activity (mSv MBq^{-1} s^{-1}) from our previous study (Han et al 2013b) into the modified NRC patient-specific equation B-5 (USNRC 2008) instead of using the exposure rate constant. If the calculated effective dose to total I-131 decay was higher than 5 mSv, the duration of radiation precautions for age-specific family members was estimated for various orientations and distances within NRC’s regulatory limit (5 mSv).

2. Methods

2.1. Modified NRC’s patient-specific dose calculations

In NUREG report no. 1556 (USNRC 2008), NRC provides the equation (B-5 in appendix U) to calculate the patient-specific radiation doses to family members at a distance of 100 cm from the patient. The expression contains three components as given below in equation (1).

\[
D(\infty) = \frac{34.6\Gamma Q_o}{r^2} \left\{ 0.75T_p(0.8) \left( 1 - e^{-\frac{0.229}{r}} \right) + \left( 0.25F_1T_{1eff}e^{-\frac{0.229}{r}} \right) \right\} + \left( 0.25F_2T_{2eff}e^{-\frac{0.229}{r}} \right)
\]

where \( \Gamma \) = exposure rate constant for a point source, R cm² MBq^{-1} s^{-1}, \( Q_o \) = administered activity, MBq, \( r \) = distance between patient and family member, 100 cm as an NRC standard value, \( T_p \) = physical half-life, in days, \( F_1 \) = extrathyroidal uptake fraction, \( T_{1eff} \) = effective half-life of extrathyroidal component, in days, \( F_2 \) = thyroidal uptake fraction, and \( T_{2eff} \) = effective half-life of thyroidal component, in days.

The first dose component was estimated for the first 8 h after I-131 administration and used an occupancy factor of 0.75. For the first 8 h, NRC assumed that 80% of the I-131 administered is to be removed from the body only by its physical half-life during the time for the I-131 to be absorbed to the blood and the hold-up of the urine in the bladder. The second dose component corresponds to the time period between the 8 h after I-131 injection and total decay using the effective half-life of the extrathyroidal component with an occupancy factor of 0.25. The effective half-life is defined as the period of time to reduce the radioactivity level of an internal organ to one half of its original value due to both biological elimination and physical decay. The third component is for the time period after the 8 h to total decay based on the effective half-life of the thyroidal component with an occupancy factor of 0.25. In this study, it is assumed that an exposure of 1 R is equivalent to an effective dose of 10 mSv. NRC also provides the uptake fractions and effective half-lives of the radioiodine treatments in their table U.6. The female gender was chosen in this study due to higher incidences of thyroidal disease in females than males (de Carvalho et al 2009).

In general, the Monte Carlo-based effective dose has been reported to be more than two-fold lower than the values obtained from the NRC method (de Carvalho et al 2009, 2011, Siegel et al 2002, Sparks et al 1998). Since the term \( (\frac{D}{r^2}) \) (R MBq^{-1} s^{-1}) in equation (1) is exchangeable with the effective dose per time-integrated activity (mSv MBq^{-1} s^{-1}) by its definition, the term \( (\frac{D}{r^2}) \) was replaced by the Monte Carlo generated \( E_{MC} \) (effective dose per time-integrated activity), which is a single dose value representing a specific patient–family member exposure scenario and the patient’s disease type (I-131 source distribution in the patient). \( E_{MC} \) was obtained from our previous (Han et al 2013b) and current study as expressed
below in equation (2).

\[
D(\infty) = 34.6Q_oE_{MC} \left\{ 0.75T_p(0.8) \left( 1 - e^{-\frac{0.529}{T_p}} \right) + \left( 0.25F_1T_{1eff}e^{-\frac{0.529}{T_p}} + 0.25F_2T_{2eff}e^{-\frac{0.529}{T_p}} \right) \right\}.
\] (2)

If the total dose from I-131 administration to total decay is higher than 5 mSv, we iteratively calculated the radiation precaution duration to limit the total dose to an individual family member to less than 5 mSv at any distance. We assumed that family members keep themselves at a distance of 100 cm from the patient for the duration of the period of i days. Equation (2) is modified again into three dose components to account for the dose during the duration of precautions: (1) the dose received for 8 h after I-131 administration at 100 cm, as shown in equation (3), (2) the dose received between 8 h and i days at 100 cm, as shown in equation (4), and (3) the dose received after i days until total decay at 10 cm, as shown in equation (5), which can be rewritten for the time i as shown in equation (6). The initial value of $t_{\text{initial}}$ (days) was estimated and the value of $t_{\text{initial}}$ then increased until the total dose obtained from equations (3)–(5) became less than 5 mSv.

\[
D \ (0 \ \text{to} \ 8 \ \text{h}) = 34.6Q_oE_{MC,100 \ \text{cm}} \times 0.75 \times T_p \times 0.8 \times \left( 1 - e^{-\frac{0.529}{T_p}} \right)
\] (3)

\[
D \ (8 \ \text{h} \ \text{to} \ i \ \text{day}) = 34.6Q_oE_{MC,100 \ \text{cm}} \times 0.25 \times \left( e^{-\frac{0.529}{T_p}} - e^{-\frac{0.693}{T_p}} \right) \times (F_1T_{1eff} + F_2T_{2eff})
\] (4)

\[
D \ (i \ \text{day} \ \text{to} \ \infty) = 34.6Q_oE_{MC,10 \ \text{cm}} \times 0.25 \times e^{-\frac{0.693}{T_p}} \times (F_1T_{1eff} + F_2T_{2eff})
\] (5)

\[
t_{\text{initial}} = \frac{\ln \left( (8.65Q_oE_{MC,10 \ \text{cm}} \times (F_1T_{1eff} + F_2T_{2eff})) - \ln(5 \ \text{mSv}) \right)}{-\frac{0.693}{T_p}}.
\] (6)

2.2. Monte Carlo generated $E_{MC}$, effective dose per time-integrated activity (mSv MBq$^{-1}$ s$^{-1}$)

The exposure scenarios included the adult female patient and family members in different postures and at different distances: (1) face to face exposures in a standing position between the patient and age-specific family members at various distances, (2) the patient and an adult family member sleeping side by side, (3) the patient holding a newborn baby, and (4) a one-year-old child standing on the lap of the patient. Two types of I-131 distribution for hyperthyroidism (HT) and differentiated thyroid cancer (DTC) patients were considered in the study. Administered activities $Q_o$ of 740 MBq (20 mCi) for an HT female patient and 5550 MBq (150 mCi) for a DTC female patient were selected as two representative cases in this study.

The term, 'family member' includes anyone who spends a substantial amount of time next to a radiiodine therapy patient, as is thus not limited to relatives, bystanders, or caregivers (NCRP 2006). A general purpose Monte Carlo code, MCNPX v2.7, was used to perform the Monte Carlo radiation transport.

2.2.1. Face to face standing exposure scenario. A female patient is facing a family member (one-, five-, and ten-year-old male, 15-year-old male and female, and adult male and female) at five different separation distances, namely 10, 50, 75, 100, and 200 cm. The distances are selected as a range that could be expected in the standing position. The effective dose per time-integrated activity ($E_{MC}$) was obtained from our previous study (Han et al 2013b).
2.2.2. Side by side sleeping exposure scenario. An exposure for an adult male partner sleeping (lying) side by side with an adult female patient, as shown in figure 1, was newly considered to evaluate the effective dose to the male partner. A separation from shoulder to shoulder of 30 cm was assumed. The effective dose per time-integrated activity ($E_{MC}$) to the male partner was obtained in this study for the two types of I-131 treatment, HT and DTC.

2.2.3. Newborn baby and one-year-old child exposure scenario. In our previous study (Han et al 2013b), the effective doses per time-integrated activity ($E_{MC}$) to a newborn baby held by the adult female patient and to a one-year-old child standing on the lap of the adult female patient were calculated. When the adult female holds a newborn, the distance from her neck to the newborn's abdomen is 18 cm, and when she cuddles a one-year-old child, the distance from her abdomen to the child's abdomen is 13 cm. By keeping the effective dose to the baby or child below 5 mSv, the duration of radiation precautions ($t$, days) was calculated using a similar method to that described in section 2.1. The NRC dose limit of 5 mSv was applied for any family member including a child, in place of ICRP or NCRPs maximum permissible dose.
(1 mSv). The reader should refer to the previous publication for a detailed graphical description (Han et al 2013b).

2.3. Dose rate measurement-to-effective dose conversion coefficients

For the face to face standing exposure scenario, the dose coefficients are provided to estimate the age-dependent effective dose to family members as a function of measured dose rate at 100 cm from the patient (mSv per mSv h\(^{-1}\)). We investigated the correlation between the measured dose rate (ambient dose equivalent rate, mSv h\(^{-1}\)) and administered activity (MBq) through literature searches. Table 1 lists the published values of measured dose rate immediately following I-131 administration at 100 cm from the patient and corresponding administered activity for both HT and DTC patients. Barrington et al (1996) explicitly provided the measured dose rate at 100 cm per administered activity from a total of 43 DTC patients. The averaged measured dose rate per activity (mSv h\(^{-1}\) MBq\(^{-1}\)) was derived from the reported data listed in table 1 as 4.195 \times 10^{-5} mSv h\(^{-1}\) MBq\(^{-1}\) for HT patients and 4.477 \times 10^{-5} mSv h\(^{-1}\) MBq\(^{-1}\) for DTC patients.

For the HT patients, in other published studies (NCRP 1996, Bernier et al 1989) the initial dose rate per activity was reported to be 5.6 \times 10^{-5} - 6.0 \times 10^{-5} (mSv h\(^{-1}\) MBq\(^{-1}\)), which is close to the I-131 exposure rate constant at 1 m, 5.946 \times 10^{6} R h\(^{-1}\) MBq\(^{-1}\). The higher dose rate per activity might be caused by the measurements being taken at the level of the patient’s neck instead of the level of the abdomen. We decided not to include these data for two reasons. First, this value should be lower than the exposure rate constant at 1 m because the exposure rate constant does not include a self-shielding effect by the anatomy of the patient. Second, the lower value gives us a more conservative estimation of the dose coefficient. However, physicists may justify the suggested dose rate per activity by comparing it with site-specific measurements.

Therefore, an age-specific dose conversion coefficient, or effective dose per measured dose rate (mSv mSv\(^{-1}\) h\(^{-1}\)) was derived as follows: the age-specific effective dose in equation (2) was converted to values of \(\frac{D}{Q_0}\) (mSv MBq\(^{-1}\)) and then this value was divided by the dose rate per activity, \(\frac{D}{Q_0}\) (mSv h\(^{-1}\) MBq\(^{-1}\)).

3. Results and discussion

3.1. Precautions for family members facing an adult female patient

Tables 2 and 3 tabulate the age-specific family member effective doses from the HT adult female patient administered with 740 MBq of I-131 and from the DTC patient with 5550 MBq of I-131, respectively, at various distances. Adult female patients can be immediately released from a hospital according to the dose limit (5 mSv) at the NRC’s standard distance of 1 m. However, it must be noted that the total effective dose could be higher than 5 mSv at shorter distances in the face-to-face exposure scenario as shown in tables 2 and 3. In this case, the duration of radiation precautions, \(t\) days, was calculated by using equations (3)–(6) and is displayed in parentheses in both tables. The duration of radiation precautions for close contact (<50 cm) needs to be addressed in an age-specific manner in the release instructions to the patient and family members. For example, as shown in table 2, the adult female HT patient should not be closer than 50 cm and should keep a separation distance exceeding 100 cm for six days with a 15-year-old and with an adult for seven days, while there is no need for radiation precautions for exposed one-, five- and ten-year-old children in standing face to face. As also shown in table 3, the adult female DTC patient should not be closer than 50 cm and should keep a distance of
<table>
<thead>
<tr>
<th>Patient type</th>
<th>Administered activity (MBq)</th>
<th>Number of patients</th>
<th>Dose rate at 100 cm (mSv h(^{-1}))</th>
<th>Dose rate per activity (mSv h(^{-1}) MBq(^{-1}))</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT</td>
<td>162.8–555 (average: 414)</td>
<td>33</td>
<td>1.88 (\times) 10(^{-2}) ± 6.3 (\times) 10(^{-3})</td>
<td>4.20 (\times) 10(^{-5}) ± 4.14 (\times) 10(^{-6})</td>
<td>Mathew et al (2004)</td>
</tr>
<tr>
<td></td>
<td>111–444</td>
<td>40</td>
<td>1.2 (\times) 10(^{-2}) ± 4.0 (\times) 10(^{-3})</td>
<td></td>
<td>Culver and Dworin (1991)</td>
</tr>
<tr>
<td></td>
<td>444–1110</td>
<td>19</td>
<td>2.9 (\times) 10(^{-2}) ± 1.2 (\times) 10(^{-2})</td>
<td></td>
<td>Culver and Dworin (1991)</td>
</tr>
<tr>
<td>DTC</td>
<td>3774–7622 (average: 5476)</td>
<td>43</td>
<td>4.6 (\times) 10(^{-5}) ± 1.4 (\times) 10(^{-5}) (\frac{\text{mSv h}^{-1}\text{MBq}^{-1}}{\text{MBq}^{-1}})</td>
<td></td>
<td>Barrington et al (1996)</td>
</tr>
<tr>
<td></td>
<td>399.6–5994</td>
<td>15</td>
<td>4.1 (\times) 10(^{-5}) ± 6.0 (\times) 10(^{-6}) (\frac{\text{mSv h}^{-1}\text{MBq}^{-1}}{\text{MBq}^{-1}})</td>
<td>4.48 (\times) 10(^{-5}) ± 3.32 (\times) 10(^{-6})</td>
<td>Groth (1998)</td>
</tr>
<tr>
<td></td>
<td>7400</td>
<td>—</td>
<td>0.35</td>
<td></td>
<td>Bushberg (2002)</td>
</tr>
</tbody>
</table>

\(^a\) The values were reported as mSv h\(^{-1}\) MBq\(^{-1}\) which is different from the others as mSv h\(^{-1}\).
Table 2. Total effective dose (mSv) and duration of post-radiation precautions for the hyperthyroidism (HT) patient who was administered with 740 MBq (20 mCi) of I-131.

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>1-year old</th>
<th>5-year old</th>
<th>10-year old</th>
<th>15-year old</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.01</td>
<td>0.62</td>
<td>3.65</td>
<td>8.27 (6 days)\textsuperscript{a}</td>
<td>8.60 (7 days)\textsuperscript{a}</td>
</tr>
<tr>
<td>50</td>
<td>0.06</td>
<td>1.26</td>
<td>2.24</td>
<td>2.75</td>
<td>2.63</td>
</tr>
<tr>
<td>75</td>
<td>0.07</td>
<td>1.06</td>
<td>1.50</td>
<td>1.67</td>
<td>1.58</td>
</tr>
<tr>
<td>100</td>
<td>0.07</td>
<td>0.83</td>
<td>1.04</td>
<td>1.11</td>
<td>1.05</td>
</tr>
<tr>
<td>200</td>
<td>0.04</td>
<td>0.34</td>
<td>0.36</td>
<td>0.36</td>
<td>0.34</td>
</tr>
</tbody>
</table>

\textsuperscript{a} The number in parentheses represents the duration of radiation protection in cases where the total effective dose is higher than 5 mSv.

Table 3. Total effective dose (mSv) and duration of post-radiation precautions for the differentiated thyroid cancer (DTC) patient who was administered with 5550 MBq (150 mCi) of I-131.

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>1-year old</th>
<th>5-year old</th>
<th>10-year old</th>
<th>15-year old</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.25</td>
<td>7.68 (1 day)</td>
<td>15.75 (10 days)</td>
<td>16.40 (12 days)</td>
<td>14.27 (9 days)</td>
</tr>
<tr>
<td>50</td>
<td>0.25</td>
<td>3.32</td>
<td>4.35</td>
<td>4.36</td>
<td>3.95</td>
</tr>
<tr>
<td>75</td>
<td>0.18</td>
<td>2.18</td>
<td>2.55</td>
<td>2.54</td>
<td>2.33</td>
</tr>
<tr>
<td>100</td>
<td>0.15</td>
<td>1.50</td>
<td>1.69</td>
<td>1.66</td>
<td>1.53</td>
</tr>
<tr>
<td>200</td>
<td>0.06</td>
<td>0.52</td>
<td>0.55</td>
<td>0.52</td>
<td>0.49</td>
</tr>
</tbody>
</table>

>100 cm when in contact with five-, ten- and 15-year olds and adults for periods of one day, ten days, 12 days and nine days, respectively.

Since the effective dose was calculated in a conservative fashion by using an occupancy factor of 0.25 even at 10 cm separation, close contact for brief periods between the patient and family members should be allowed. The effective doses for any other amount of administered activity (Q, MBq) can be calculated in tables 2 and 3 by multiplying $\frac{Q}{20 \text{ mCi}}$ for an HT patient and $\frac{Q}{150 \text{ mCi}}$ for a DTC patient.

3.2. Precautions for a partner sleeping with a patient

The total effective dose to an adult male from sleeping side by side at 30 cm with an adult female patient is 0.643 mSv for the HT patient and 1.508 mSv for the adult female DTC patient, respectively. Radiation precautions are not required for this particular exposure scenario.

However, if either the patient or the partner happens to be a side sleeper, the partner should keep a distance of at least 50 cm for ten days from the shoulder of the HT patient and for 20 days for the DTC patient. For this calculation, the $E_{MC}$ of an adult phantom at 50 cm in the face to face standing position was used in equations (3) and (4) and the $E_{MC}$ of the adult phantom at 10 cm was used in equation (5). During this period, sexual intercourse is discouraged.

3.3. Precautions for a newborn baby and a one-year-old child exposed to an adult female patient

Table 4 presents the effective dose per time-integrated activity, effective dose and duration of radiation precautions for a newborn and a one-year-old child with an HT or DTC adult female patient. The values of effective dose per time-integrated activity were adopted from our previous study (Han et al 2013b) where realistic Monte Carlo simulations of mother and baby/child exposure scenarios were performed for the first time. As shown in table 4, an HT female patient who was administered with 740 MBq of I-131 should avoid holding a newborn
Table 4. Effective dose (mSv) to a newborn and a one-year-old child from an adult female patient treated for hyperthyroidism (HT) or differentiated thyroid cancer (DTC).

<table>
<thead>
<tr>
<th>Exposure scenario</th>
<th>Effective dose per time-integrated activity (mSv MBq(^{-1}) s(^{-1}))</th>
<th>Effective dose (mSv)</th>
<th>Duration of radiation precautions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newborn with HT patient</td>
<td>1.91 \times 10^{-7}</td>
<td>20.5</td>
<td>16 days at &gt; 100 cm</td>
</tr>
<tr>
<td>Newborn with DTC patient</td>
<td>1.44 \times 10^{-7}</td>
<td>29.6</td>
<td>15 days at &gt; 100 cm</td>
</tr>
<tr>
<td>One-year old with HT patient</td>
<td>2.78 \times 10^{-7}</td>
<td>3.0</td>
<td>N/A</td>
</tr>
<tr>
<td>One-year old with DTC patient</td>
<td>1.46 \times 10^{-7}</td>
<td>3.0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 5. Dose conversion coefficients (mSv mSv\(^{-1}\) h\(^{-1}\)) for family members exposed to an adult female patient treated for hyperthyroidism.

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>1-year old</th>
<th>5-year old</th>
<th>10-year old</th>
<th>15-year old</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>0.32</td>
<td>20.11</td>
<td>117.66</td>
<td>266.56</td>
<td>277.18</td>
</tr>
<tr>
<td>50 cm</td>
<td>1.92</td>
<td>40.45</td>
<td>72.30</td>
<td>88.57</td>
<td>84.57</td>
</tr>
<tr>
<td>75 cm</td>
<td>2.32</td>
<td>34.06</td>
<td>48.19</td>
<td>53.81</td>
<td>50.91</td>
</tr>
<tr>
<td>100 cm</td>
<td>2.30</td>
<td>26.89</td>
<td>33.58</td>
<td>35.86</td>
<td>33.87</td>
</tr>
<tr>
<td>200 cm</td>
<td>1.13</td>
<td>10.80</td>
<td>11.72</td>
<td>11.68</td>
<td>10.99</td>
</tr>
</tbody>
</table>

Table 6. Dose conversion coefficients (mSv mSv\(^{-1}\) h\(^{-1}\)) for family members exposed to an adult female patient treated for differentiated thyroid cancer.

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>1-year old</th>
<th>5-year old</th>
<th>10-year old</th>
<th>15-year old</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm</td>
<td>0.96</td>
<td>30.09</td>
<td>61.68</td>
<td>64.25</td>
<td>55.90</td>
</tr>
<tr>
<td>50 cm</td>
<td>0.98</td>
<td>13.00</td>
<td>17.04</td>
<td>17.09</td>
<td>15.45</td>
</tr>
<tr>
<td>75 cm</td>
<td>0.72</td>
<td>8.54</td>
<td>9.99</td>
<td>9.97</td>
<td>9.15</td>
</tr>
<tr>
<td>100 cm</td>
<td>0.57</td>
<td>5.87</td>
<td>6.63</td>
<td>6.51</td>
<td>6.00</td>
</tr>
<tr>
<td>200 cm</td>
<td>0.23</td>
<td>2.03</td>
<td>2.17</td>
<td>2.04</td>
<td>1.91</td>
</tr>
</tbody>
</table>

to her chest for 16 days. A DTC patient should not hold a newborn against her chest for at least 15 days. During that period, the patient should keep a distance of at least 100 cm from her newborn baby. In this calculation, the $E_{MC}$ of a one-year-old phantom at 100 cm from the adult female phantom in standing position was used in equations (3) and (4). Infrequent holding or hugging of a newborn or child for a brief moment should be allowed.

3.4. Dose rate measurement-to-effective dose conversion coefficients

Dose conversion coefficients (mSv/mSv h\(^{-1}\)) were tabulated for the HT and DTC adult female patients as given in tables 5 and 6, respectively. A physicist can convert their survey meter or ion chamber readings (ambient dose equivalent rate, mSv h\(^{-1}\)) to age-specific effective dose (mSv) at various distances. In other words, after a site physicist has measured a dose rate at 100 cm from the mid-abdomen of a patient after I-131 administration, he or she can multiply the measured dose rate by the dose conversion coefficient in tables 5 and 6 to estimate the age-specific effective dose. The effective dose provides the physicist with patient and family member specific release guidance.
3.5. Limitation of the study

In this study, it is assumed that the TEDE is equal to the effective dose equivalent (EDE). If ICRP or NCRPs maximum permissible dose (1 mSv) is applied as the dose limit for the baby/child instead of 5 mSv, the radiation protection duration might be increased to five times more than suggested in section 3.3. In all exposure scenarios, an occupancy factor of 0.25 was selected for the dose calculation, but a site physicist can justify the factor in a case by case approach for each patient.

4. Conclusions

Patients administered with I-131 of less than 740 MBq for HT or less than 5550 MBq for DTC treatment can be immediately released using NRC’s standard. However, there are durations for radiation precautions for close contact which need to be addressed in the release instructions considering the age/height of family members. A site physicist can project the effective dose and the exposure avoidance durations by utilising the equations provided in this study with justifiable values of the occupancy factor at various exposure distances. The HT adult female patient should avoid holding a newborn to her chest for 16 days and the DTC female patient should not hold her newborn for 15 days. Due to high uptake fractions and lower effective half-life, a physicist should not overlook radiation precautions for an HT patient with even a relatively smaller amount of I-131 administration than a DTC patient. We have also provided the dose conversion coefficients to convert survey meter readings (mSv h⁻¹) to age-specific effective doses (mSv). The physicist can provide family members with age-specific radiation precaution guidance for various exposure postures and distances. Effective dose-based release criteria with a modified NRC two-component model provide a site physicist with less restrictive and patient-specific guideline as they consider both general patterns of patient radiiodine biokinetics and photon attenuation by both the source patient and exposed family members.

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