ESTIMATION OF EXTERNAL RADIATION DOSE TO CAREGIVERS OF PATIENTS TREATED WITH RADIOIODINE AFTER THYROIDECTOMY

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Abstract—**Due to the remarkable increase in thyroid cancer cases, the number of patients treated with radioiodine (^{131}I) shows a sharply increasing trend in recent years. Accordingly, radiation exposure of other people, particularly caregivers or comforters, after release of patients from hospitals is getting more attention than ever. In the present study, empirical equations are proposed for estimation of doses to caregivers. Only patients administered with therapeutic amounts of ^{131}I after thyroidectomy were considered. External radiation doses to 70 caregivers or family members were measured using thermoluminescence dosimeters (TLDs). The mean, external, effective dose to caregivers, during a nursing period of 5–9 d after patient quarantine for 3–4 d in the hospital, was 0.12 ± 0.10 mSv. This is only 2.5% of the dose limit recommended by the International Commission on Radiological Protection for caregivers. By analyzing those individual doses to the caregivers, values of a factor affecting caregiver doses, *K*, are obtained for use in estimation of caregivers' doses. The factor reflects the degree of engagement of the caregiver to the patient, and hence it is named the "engagement factor." The mean value of the engagement factor in this study was 1.3 ± 0.88. With the help of the engagement factor, the total external dose to a caregiver can be estimated as $1.1 \times Q_0 \times e^{-0.05Tr}$ mSv, where Q_0 is the administered activity of ^{131}I (GBq) and T_r is the patient's release time (h) after admistration of radioiodine. Based on the dose estimation model developed in this study, by comparing the cost of extended quarantine against that incurred by release of the patient, including the burden of radiation exposure of caregivers or family members, the reasonableness of current quarantine periods was revisited. It was found that the dichotomous policy (i.e., hospitalizing patients administered ^{131}I over 1.1 GBq for a period of 3–4 d compared with treating other patients administered below 1.1 GBq as outpatients) is unjustifiable; this is particularly true for those treated with a few GBq. Based upon the dose estimation model presented herein, tables suggesting an appropriate quarantine period depending upon the activity of the administered ^{131}I are provided for use as reference in deciding when to release patients treated with therapy levels of ^{131}I after thyroidectomy.**

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INTRODUCTION

VERY POSITIVE prognosis has resulted from standard treatment of thyroid cancer using radioiodine, rather than thyroid stimulating hormone (TSH), to treat patients after thyroidectomy. One precaution, however, is that radiation exposure inevitably occurs to those persons in the vicinity of the patients, either during the time of treatment or in subsequent patient care. Recommendations of the International Commission on Radiological Protection (ICRP), Publication 60 (ICRP 1991), and the standards of the International Atomic Energy Agency (IAEA) as recommended in IAEA Safety Guide No. RS-G-1.5 (IAEA 2002), stipulate a dose limit of 1 mSv y^{-1} to the general public and 5 mSv y^{-1} to relatives, visitors, and caregivers who are exposed to patients treated with therapeutic amounts of radiopharmaceuticals. Further, ICRP Publication 94 (ICRP 2004) recommends an annual dose limit of 1 mSv to embryos, bereaved children, and children, a group of persons with higher sensitivity to radiation, in lieu of the dose limit of 5 mSv y^{-1}.

The federal regulation of the Nuclear Regulatory Commission in the United States, Regulatory Guide 8.39 (U.S. NRC 1997), stipulates that the residual radioactivity shall be no more than 1.22 GBq and that an ambient dose rate be no more than 70 μSv h^{-1} at a distance of 1 m from the patient. This is an effective dose equivalent of 5 mSv, applicable to other persons who suffer any exposure during isolation and/or after release from the hospital of patients treated with high-activity radioiodine. The Korean standards for allowing release from the hospital of patients treated with radioiodine are similar to those in the U.S., and safety control practices pursuant to those standards are applied to nuclear medicine departments of most hospitals in Korea.

Several precedent research cases exist for radiation dose levels in the vicinity of patients treated with radioiodine. Pant et al. (2006) evaluated the effective dose to family members of thyroid cancer patients treated with 0.9–7.4 GBq. Thermoluminescence dosimeters (TLDs) were used for measuring whole-body dose to 297 family members of thyroid cancer patients. In addition, 103 family members of thyroid cancer patients were monitored for dose assessment to their thyroid gland. The results indicated that 76% of the family members had been exposed to less than 1.0 mSv, with an average dose to all family members of ~ 0.7 mSv. All family members except one had measures of 5.0 mSv or lower. The dose level of the single exception was 8.5 mSv, who was the only caregiver of a patient that was incapable of moving. In 2009, Carvalho et al. (2009) monitored radiation exposure to 27 adult family members of 20 thyroid cancer patients treated with 3.70–5.55 GBq on an outpatient basis. Radiation exposure to family members was evaluated with TLDs. The results indicated a dose of 1 mSv or lower except for one family member. The radiation dose to that family member was 2.8 mSv, indicating that it was still within the guidelines for exposure to family members, even in patients treated as outpatients having high radioiodine activity.

The purpose of this study is to propose a means for upgrading care systems for thyroid cancer patients measuring doses received by caregivers and developing a model for predicting doses to caregivers in accordance with the levels of radioactive iodine administered. Previous research has indicated that radiation dose varies greatly among caregivers, so that it is expected that the development of a model for predicting dose will be subject to limitations. Indeed, there are significant variations to take into account related to the nature of the care and nursing provided, as well as to applications of the guidelines and recommendations for care in hospitals. However, it is assumed herein that there are patterns of exposure based on the amount of time that the caregiver spends in the vicinity of the patient as well as on the distance of the caregiver from the patient. Based on these assumptions, it has been anticipated that exposure to caregivers is predictable when defining characteristics of degree (distance and duration) of contact between patients and caregivers have been specified.

MATERIALS AND METHODS

Theoretical background for estimation model of effective dose to caregivers

Dose rate over time is reduced exponentially with increasing distance from the ^{131}I-administered thyroid cancer patient after thyroidectomy, as shown in Fig. 1. The external radiation dose is measured at a reference distance of 1 m for an interval extending from the time the patient leaves the hospital, T_r (end of quarantine period), until the time that monitoring the patient ends, T_m, after administration of a specific activity of ^{131}I to the patient following thyroidectomy. During this period of patient isolation, the external radiation dose to the patient can be defined as an integration of the dose rate, $\dot{H}_o(t)$, at the reference distance, from T_r to T_m:

$$H_o = \int_{T_r}^{T_m} \dot{H}_o(t)dt. \quad (1)$$

Assuming a pattern of exposure conditions between caregiver and patient, it is reasonable to relate ambient dose, H_o, to the dose to caregivers (H_c) at the reference distance with a certain parameter K:

$$H_c = K \times H_o. \quad (2)$$

Meanwhile, the ambient dose rate at 1 m from the ^{131}I-administered patient can be obtained by:

$$\dot{H}_o(t) = \Gamma_P Q_0 \, e^{-\lambda_{eff} t}. \quad (3)$$

Here, the constant Γ_P is the ambient dose equivalent rate coefficient at a distance of 1 m from the patient per unit administration activity (GBq), which has been suggested, based upon measurement, as 4.3×10^{-2} mSv h^{-1} GBq^{-1} (Kim et al. 2012). The constant Γ_P is also called the "radioiodine patient gamma constant" in this study. Q_0 is the initial administered activity of ^{131}I (GBq). An effective removal constant (λ_{eff}) for the ^{131}I (h^{-1}) is included. When applying the effective half-life of 13.9 h (= 0.58 d) of ^{131}I (Kim et al. 2012) to thyroidectomy patients, 0.05 h^{-1} (= 1.2 d^{-1}) can be used as λ_{eff}.

Linking the dose rate eqn (3) containing the radioiodine patient gamma constant (Γ_P) with eqn (1), an equation can be derived for predicting external dose to persons in the vicinity of patients, dependent upon the activity administered to the patient. External dose (H_c) to family

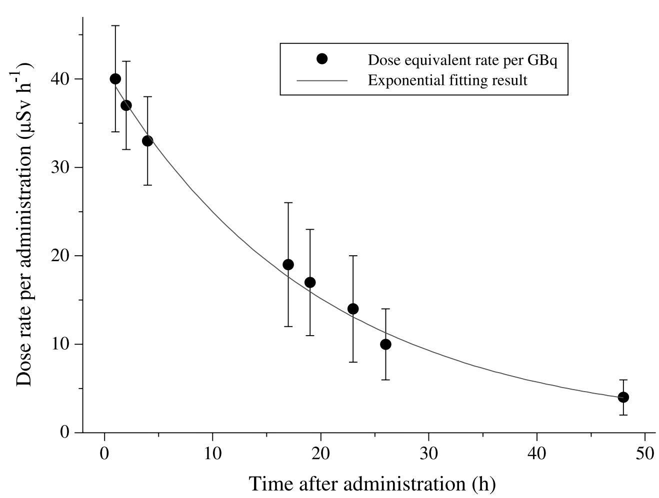


Fig. 1. Dose rates measured at 1 m in front of patients and their fit as a function of time (Kim et al. 2012).

members or caregivers after patients have been released from hospitals can be estimated from the initial activity, Q_0, of ^{131}I administered; end of quarantine period (T_r); and end of dose measurement (nursing) period (T_m):

$$\begin{aligned} H_c &= K \times H_o = K\int_{T_r}^{T_m} \dot{H}_o(t)dt \\ &= K \times Q_0 \times \Gamma_P \int_{T_r}^{T_m} e^{-\lambda_{eff}t}dt \\ &= \frac{K \times Q_0 \times \Gamma_P}{\lambda_{eff}}\left[e^{-\lambda_{eff}T_r} - e^{-\lambda_{eff}T_m}\right]. \end{aligned} \quad (4)$$

The actual exposure period for measurement was a minimum of 5 d, while the effective half-life of the radioiodine was 14 h, as discussed in the previous study (Kim et al. 2012). Therefore, virtually all radiation exposure ended within the nursing interval, since residual radioactivity inside the patient's body by the end of this period was barely 0.25% of the initial level present when leaving the hospital. This prediction is described in more detail in the next section. From this, it is reasonable to consider the second, or upper, time limit in the exponential integrated interval in eqn (4), which is insignificant compared to the first. Consequently, the total predicted dose of radiation exposure to caregivers during treatment of patients at home after release from hospitals is estimated as follows:

$$\begin{aligned} \dot{H}_{c,\infty} &= \frac{K \times Q_0 \times \Gamma_P \times e^{-\lambda_{eff}T_r}}{\lambda_{eff}} \\ &= 0.86 \times K \times Q_0 \times e^{-0.05T_r}(mSv). \end{aligned} \quad (5)$$

Since the radioiodine patient gamma constant reflects the dose rate 1 m from the front of the patient and 1 m above the floor, the actual dose rate from ^{131}I widely distributed over the whole body is inevitably lower than that of a point source due to distance effects from the physique of both patient and caregivers, as well as shielding effects caused by the human body.

Effective dose measurement of caregiver

Radiation dose to caregivers of patients released from hospitals after radioiodine treatment following thyroidectomy was measured using TLDs. The targets of measurement were 70 caregivers of patients administered between 3.7–7.4 GBq of ^{131}I at two university hospitals in Korea. All patients who underwent thyroidectomy were included in these measurements except patients having abnormal kidney functions.

The TLD used was in the form of a personal dosimeter with attached UD-874ATM holder (Panasonic Communications Kyushu Co., LTD, 2111 Ueda Usa, Oita 879-0493, Japan). This personal dosimeter was approved by a type test executed by a regulatory authority, in which an expert institute performed a regular capability examination of the reading on the dosimeter. The minimum detectable dose of the dosimeter was 0.01 mSv.

Personal dosimeters were issued to the primary caregivers of the patients. The reason for selecting only one primary caregiver per patient was that one primary caregiver, in most cases, takes care of a patient for several days, according to the results of a preliminary survey. If two caregivers were taking care of one patient, the caregiver taking care of the patient for the longer time was instructed to wear the dosimeter.

The caregivers were instructed to wear the dosimeter on their chest, as done by radiation workers, and to place the dosimeter beside their pillows during sleep, so as not to underestimate the dose due to possible displacement during sleep. All the caregivers that participated in the study slept in a room apart from the patient. Instructions for use of the personal dosimeter were given to caregivers and family members of patents released from the hospital, both verbally and in writing. These instructions were provided to caregivers and family members at the same time as the instructions and precautions for patient care and the explanation of the background of the patient.

Hospital staff issuing the dosimeters were instructed to record administered activity to the patient, administration date, serial number of the dosimeter, release date of patient from hospital, and return date for the dosimeter. The dosimeter bearer was instructed to return the dosimeter when the patient visited the hospital after the dosimeter usage period (5 to 9 d, dependent upon the patient's condition). The collected dosimeter was checked for any external contamination and then read. The actual exposure comes from various angles, but the authors have not considered the angular dependence of the TLD because they judged that it would not make any significant change to the results or conclusions, as explained in the following sections on uncertainty.

Uncertainty for measurement of whole body effective dose equivalent of caregivers

Total expansion uncertainty (U_T), described in detail below, affects assessment and calculation for estimating the effective dose of caregivers. The factors entering U_T include uncertainty in the measurement of the TLD itself (U_1), uncertainty of quarantine period (U_2), uncertainty of period for wearing the dosimeter for assessment of persons in the vicinity of patients after release from the hospital (U_3), uncertainty of radioiodine administrated activity (U_4), and uncertainty of geometrical configuration of sources (U_5). Assuming statistical independence of the factors, the total uncertainty (U_T) can be expressed as:

$$U_T = \sqrt{U_1^2 + U_2^2 + U_3^2 + U_4^2 + U_5^2}. \quad (6)$$

Values used for U_1 to U_5 are presented in the Results section, below.

Pattern of patient care and timing of exposure

A questionnaire survey was conducted to identify patterns of patient care by caregivers, and the radiation dose was measured making use of an active electronic personal dosimeter (Model Thermo EPD-G). In general, the number of female patients far surpasses the number of male patients (70–80% of all patients are female), and caregivers are typically close family members such as spouses, parents, and sisters. A patient typically stays at home for 5−6 d after release from the hospital. The patient generally goes out once or twice a day for 1 h during treatment at home. During treatment at home pursuant to guidelines, the patient does not have any contact with children or babies and uses a single bedroom.

RESULTS

Measurement results of caregiver dose

Fig. 2 illustrates the frequency histogram of doses received by caregivers, measured by TLD, who took care of patients at home after they were released from the hospital. As shown in the figure, the frequency histogram of doses received by caregivers is similar to a log-normal shape, with distribution biased toward low doses rather than assuming the normal, symmetrical distribution. The major statistics of this distribution are shown in Table 1, which shows an arithmetic mean of 0.12 mSv, standard deviation of 0.10 mSv, geometric mean of 0.091 mSv, and geometric standard deviation of 2.1. The median is 0.085 mSv, the maximum 0.50 mSv, and the minimum 0.02 mSv. These results were similar to the mean doses of 0.4–0.8 mSv reported by Pant et al. (2006) and 0.01–0.17 mSv reported by Park (2008).

The fact that the distribution of caregiver dose in Fig. 2 is asymmetric, biased low-to-high dose and not symmetric from the mean value, means that the relationship between caregiver and patient may have some random deviation from the mean pattern. The resultant dose means that a particular pattern of care may cause higher or lower exposure (e.g., an exceptionally close relationship between patient and caregiver may increase the exposure) from the typical pattern of approximately 0.1 mSv. Despite some modest bias toward lower value, the arithmetic mean was used in the development of a dose prediction model in the next section for the purpose of guaranteeing conservativeness.

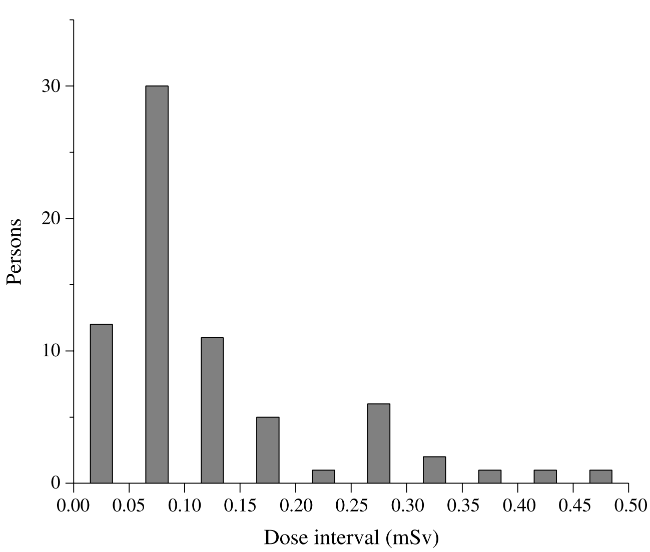


Fig. 2. Frequency distribution of caregiver dose.

Table 1. Analysis of the dose measurement to caregivers.

Statistics[a]	Administered activity (GBq)	Quarantine period (days)	Measurement duration (days)	Effective dose (mSv)
Arithmetic mean	5.0	3.2	6.7	0.12
Standard deviation	1.1	0.42	0.94	0.10
Geometric mean	—	—	—	0.091
Geometric standard deviation	—	—	—	2.1
Median	5.6	3.0	7.0	0.085
Maximum	7.4	4.0	9.0	0.50
Minimum	3.7	3.0	5.0	0.020

[a]Microsoft excel software was used.

A maximum of 5% uncertainty is expected in the measurement. A maximum of 3% of uncertainty is expected in the admission period of patients, since hours for admission to and release from the hospital did not exceed 2 h for 72 h of hospitalization of an individual patient. Next, a maximum of 4% uncertainty is expected for the approximately 168-h interval from the start of wearing the dosimeter until reading the dosimeter for dose assessment, since this period did not exceed 6 h. Uncertainty for the radioiodine administration activity is controlled typically within ±10% in the course of production and consumption, and uncertainty about the geometric configuration of the source is not expected to exceed 15% when considering the previous results. Therefore, it is expected that the total expansion uncertainty will not exceed 20% when using eqn (6). Note that uncertainty in the standard deviation results from differences in the metabolic rates of individual patients. Variations due to conditions related to how the dosimeters are worn and uncertainty about the total time the dosimeters are worn by caregivers are not considered.

Table 2 shows the expected amounts of exposure to caregivers after patients are released from the hospital. This took into account the hospitalization period and activity level of the radioiodine administered to patients, derived from the values of engagement factors, based on the prediction model developed in this study. It shows the expected exposure dose to caregivers calculated from engagement factors in the 95th percentile. The exposure dose will increase for caregivers of patients with a prolonged, internal retention time of radioiodine in the top 5% of the treated population. Significantly slower metabolism, compared to normal healthy human beings, will increase the radiation dose to caregivers radically compared to that of patients with average metabolism. Therefore, it is reasonable to make conservative predictions of the exposure dose to caregivers when applying this table. The table indicates that patients administered radioiodine of less than 7.4 GBq do not cause radiation doses above the limit of 5 mSv to persons in the vicinity of the patient from hospitalization for one full day (24 h). Table 2 is a useful reference for application to radiation protection, such as in the selection of hospitalization period dependent upon the activity level of the radioiodine administered to the patient, and also in the improvement of safety controls and reduction of exposure to radiation through education of patients and caregivers.

Pattern of patient care and timing of exposure

Caregivers almost always stay in the vicinity of the patients for periods of time while caring for them, but they may spend the majority of their time in other rooms or spaces in a house, remote from the patient. Caregivers typically come into close contact with patients two or three times a day, at the least, to provide meals and medication. The average duration of close contact with patients by caregivers was 2 h d^{-1}, and the longest duration was 4 h d^{-1}. Most caregivers share a minimum of two meals out of three each day with the patient, with each meal taking approximately 30 min. Other than having meals together with the patient, the caregiver usually conducts leisure activities and stays with the patient for approximately 30 min a day, including medication and chores for the patient. These survey behaviors of patients and caregivers appear consistent with the guidelines and education data of hospitals, which are almost identical among hospitals.

Figs. 3 to 5 illustrate the distribution of dose, by time slot, of caregivers wearing active personal dosimeters, for patients A to C. The time available for measuring dose on an active personal dosimeter is approximately 2 wk (14 d) after charging the electronic dosimeter. Caregivers were instructed not to turn off the power to the dosimeter; this is only done by the physician after the patient returns the dosimeter to the hospital.

Three female patients provided assistance for assessment of doses to caregivers wearing the active personal dosimeter. Patient A was 36-y old, and her caregiver was her 64-y-old father. Patients B and C were 35 and 41-y old, respectively, and their caregivers were their spouses (male). The ages of the caregivers of Patients B and C were similar to that of other patients. The father of Patient A visited the hospital when the patient was to be released from hospital and went home together with the patient. The time of release of Patients A and C from the hospital was 11:30 in the morning (immediately before lunch break). The caregiver of Patient A accompanied the patient when the patient was released from the hospital and spent approximately 2 h with the patient, including having lunch. Most of the exposure to the caregiver took place during those 2 h. The total radiation dose of the caregiver of Patient A was 0.06 mSv, and the exposure during approximately 1 h in the company of the patient on the way to the patient's home was estimated at 0.03–0.04 mSv. The balance of the amount of 0.02–0.03 mSv was considered generated while the caregiver had lunch with the patient. It was observed that additional exposure of the caregiver of Patient A did not take place because there was no further contact between the patient and her caregiver. Patient A visited the hospital alone for treatment, and the dosimeter brought by the patient read no particular exposure amount, which indicated significant reduction of dose rate of the patient on the fifth day after release from the hospital (approximately 7th or 8th day after administration of radioiodine).

No noticeable increase of dose from the caregivers of Patients B and C was identified, even though they went home together with the patients. It was assumed that the caregivers strictly observed radiation protection principles of keeping a remote distance from the patient or that it did

Table 2. Caregiver's effective dose for K=2.35, upper 95 percentile K (mSv).[a]

Patient hospitalization duration (d)	Administered activity (GBq)												
	0.37	1.1	1.9	3.0	3.7	4.4	5.6	6.7	7.4	8.1	9.3	10	11
0	0.87	2.6	4.3	7.0	8.7	10	13	16	17	19	22	24	26
1	0.26	0.79	1.3	2.1	2.6	3.1	3.9	4.7	5.2	5.8	6.5	7.3	7.9
2	0.08	0.24	0.39	0.63	0.79	0.95	1.2	1.4	1.6	1.7	2.0	2.2	2.4
3	0.02	0.07	0.12	0.19	0.24	0.29	0.36	0.43	0.48	0.52	0.59	0.67	0.71
4	0.01	0.02	0.04	0.06	0.07	0.09	0.11	0.13	0.14	0.16	0.18	0.20	0.21
5	0.00	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.07
6	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01

[a]Shaded block > dose limit of 5 mSv.

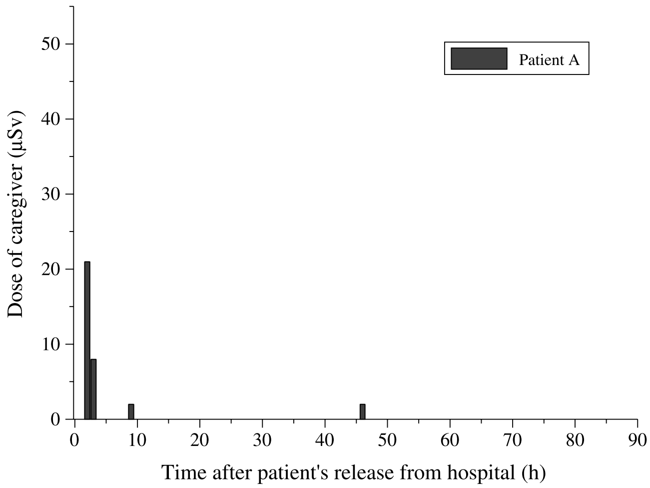


Fig. 3. Patterns of the dose to the caregiver of patient A for every hour after the patient's release, measured by the active personal dosimeter.

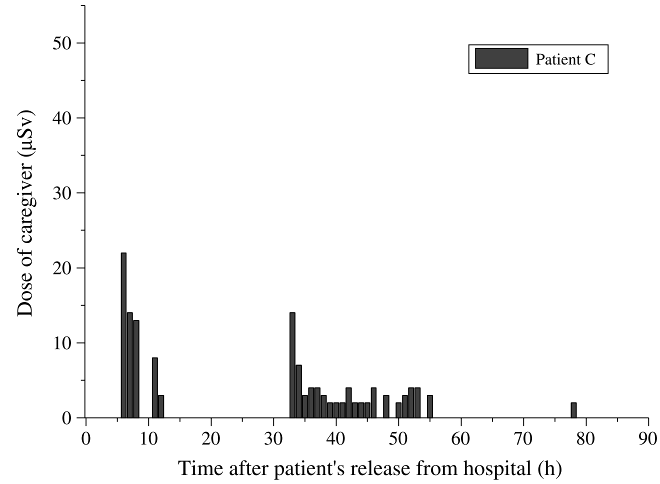


Fig. 5. Patterns of the dose to the caregiver of patient C in hours after release of the patient, measured by the active personal dosimeter.

not take long to get home together after release of the patients from the hospital. However, young Patient B and her caregiver often talked up to 4 h a day. The radiation dose of the caregiver for 5 h during the night of the first day of release from the hospital until 3:00 in the morning of the next day, reached approximately 0.11 mSv, which is equivalent to approximately 60% of the total exposure amount (0.19 mSv). Relatively high exposure took place to the caregiver during the lunch break and in the afternoon of the next day. However, no exposure took place at night, since the patient and the caregiver slept in separate rooms. It was assumed that Patient B was strictly isolated or kept at a relatively safe distance away from the caregiver except during direct contact, and that pattern carried on for subsequent days. Accordingly, the radiation dose to the caregiver started to decline rapidly from the third day and

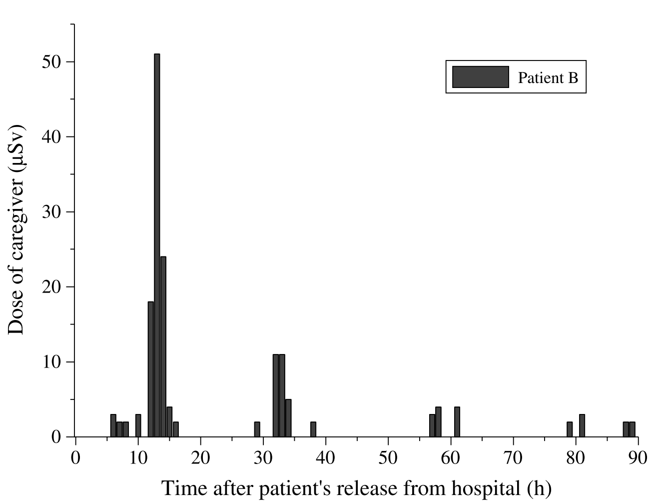


Fig. 4. Patterns of the dose to the caregiver of patient B in hours after the patient's release, measured by the active personal dosimeter.

thereafter. The patient visited the hospital for the next treatment together with the caregiver. However, the radiation dose indicated for the caregiver was extremely low compared with that on the day the patient was released from the hospital.

Patient C and her caregiver were a middle-aged couple. Most of the dose to the caregiver took place within 1 d after release from the hospital, showing similar behaviors to that of Patient B. However, the caregiver of Patient C did not indicate exposure concentrated in a specific time at the adjacent location as shown for the caregiver of Patient B, and it was assumed that the caregiver of patient C kept a safe distance away from the patient, other than to have lunch and interact with the patient. The caregiver of Patient C was exposed to a total of 0.18 mSv, similar to that of the caregiver of Patient B. The radiation dose of the caregiver to Patient C was drastically reduced 2 d after release from hospital, with no additional exposure to the caregiver imminent since Patient C visited the hospital alone for treatment. These patient care patterns were generally consistent with some variation depending upon the relationship between patient and caregiver, familiarity between patient and caregiver, and the physical condition of the patient. In particular, radiation dose of caregivers was noticeably reduced by the third day (beginning 48 h after release of the patient from the hospital). Concentrated radiation dose of caregivers may take place in automobiles or public transportation when caregivers go home together with patients after their release from the hospital and during the first and the second days at home when caregivers provide patients with concentrated care and when the patient would be less mentally stable. Going home takes longer if the home of the patient is in the countryside or in a city away from where the patient was administered high-activity radioiodine. In such a case, the caregiver may accompany the patient for 5 h or longer, and caregivers may be exposed to 0.15–0.30 mSv within a few hours after release of the patient. In particular, if caregivers remain in close proximity to patients, such as in automobiles or public transportation, for an extended period of time, internal and external exposure to caregivers, caused by exhalation, sweat, and saliva of the patient, may exceed 1 mSv during the process of going home from the hospital. Additional examination and careful analysis for these situations are required.

It is not possible to generalize patient care patterns from the three cases described above. However, it is expected that patterns of care may vary depending upon physical conditions and behavioral conditions of the patient, familiarity between patient and caregiver, distance maintained, and duration of contact. As described in this section, caregivers receive the most radiation dose in the first and second days after the patient is released from the hospital. Overall radiation dose of caregivers will generally be greater than the mean dose if travel from hospital to home is prolonged, independent of the actual distance.

DISCUSSION

Comparison of intake retention function to oral intake over time

Thyroid cancer patients are administered high-activity radioiodine to kill cancer cells left after 90% or greater resection of the thyroid. Iodine uptake at the thyroid virtually does not take place for patients having thyroidectomy. Therefore, with less iodine uptake, the internal retention time of radioiodine for a patient is shorter than that for normal human beings. This indicates the possibility of sufficient regression analysis using only a single exponential function. This means that the thyroid model of ICRP suggested for normal human beings is not applicable to patients after thyroidectomy.

The behavior of iodine inside the body of a human being with normal thyroid function is not indicated by a simple primary linear exponential function. Therefore, it is difficult to suggest an effective half-life with a simple value. Radioiodine remains for a relatively long period of time in the iodine-friendly thyroid. For healthy human beings, it takes 13 h to reduce the amount of radioiodine, retained internally after oral intake, down to 50% of the amount administered initially, 39 h to 25%, and 184 h to 12.5%. This points to varying half-lives. One method for choosing a single value for half-life is the use of the geometric mean of the half-life at 45 h, which is significantly different from the half-life at 14 h obtained from thyroidectomy patients.

Since the thyroid is a small organ of a mere 20 g, it is reasonable to assume that the source is a point source, even if the source is really distributed throughout the thyroid, when comparing it to the volume and mass of a healthy human being. However, it is necessary to examine the radioactivity in the thyroid compared to other organs and the change of radioactivity in the thyroid over time. Radioiodine is maintained at high concentrations in the kidneys, bladder, and blood within 1 d of oral intake of radioiodine, and it is necessary to compare volumetric distribution of radioiodine in the blood system with that in the thyroid. The blood system, consisting of arteries, veins, and peripheral blood vessels, is distributed throughout the body, so that it is reasonable to assume that the distribution of radioactive materials in the blood is a volumetric source.

Therefore, one cannot assume the source of the radiation to be a point source after 90% or more of the thyroid has been removed by the thyroidectomy. It is necessary to compare the distribution over time of radioiodine in the major organs, using conditions of point sources and volumetric sources to estimate distribution curves of such sources. The results from calculation of the intake retention fraction of the major organs to identify variation in levels of internal radioiodine over time are shown in Fig. 6.

Table 3 shows the retention fraction after oral intake of ^{131}I on major organs of healthy human beings at intervals of 6 h over a 48-h period. Radioiodine distributed in the blood is reduced rapidly over time and deposited in the thyroid, and most of radioiodine inside the body is accumulated in the thyroid, which becomes saturated after 24 h.

As shown in Fig. 6 and Table 3, the level of internal radioiodine in major organs, after oral intake for treatment of thyroid disease, is distributed as follows: 70% of the whole body intake in blood and 17% of whole body intake in thyroid 6 h after intake. However, these fractions change rapidly over time, so that after 24 h, approximately 19% of the whole body intake remains in the blood, and 74% of

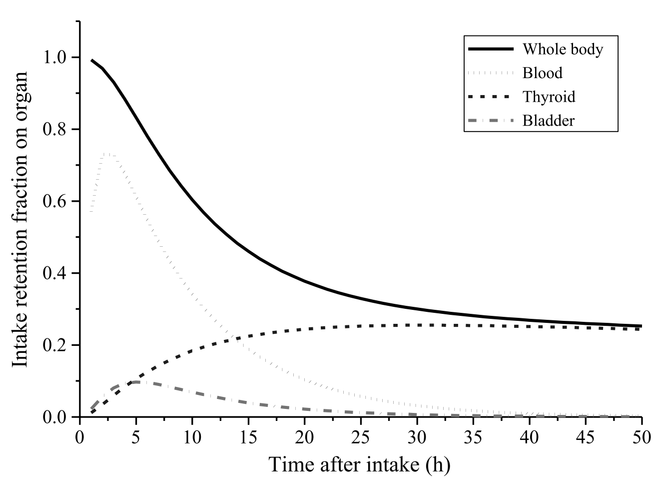


Fig. 6. Trend of intake retention fractions for ingestion of ^{131}I as a function of time.

Table 3. Intake retention fraction for ingestion of ^{131}I.

Organ of interest	Retention fractions			
	Time after intake (h)			
	6 (1/4 d)	12 (1/2 d)	24 (1 d)	48 (2 d)
Whole body	0.78	0.54	0.34	0.26
Blood	0.55	0.27	0.065	0.004
Thyroid	0.13	0.20	0.25	0.25
Bladder	0.095	0.056	0.015	0.001

the whole body intake has been stored in the thyroid. After 48 h, a mere 1.5% is retained in the blood, which is no longer considered a volumetric source, since the distribution of radioiodine is close to zero in the blood of a patient leaving the hospital after isolation for 3 d. However, this distribution is based on the metabolic model of a healthy human being, not that of a patient after thyroidectomy, and the distribution of radioiodine in the patient will definitely not be similar to that of a healthy human being. In particular, for thyroid cancer patients, after 90% or more of the thyroid has been removed, the retention of radioiodine in the thyroid is insignificant.

Factors affecting caregiver dose

Eqn (2) above defines the dose rate to caregivers for the reference dose in the vicinity of the patient, as a factor *K*. Eqn (4) can be rearranged for factor *K* as follows:

$$K = \frac{\lambda_{eff}}{Q_0 \times \Gamma_P} \times \frac{H_c}{e^{-\lambda_{eff} T_r}}. \qquad (7)$$

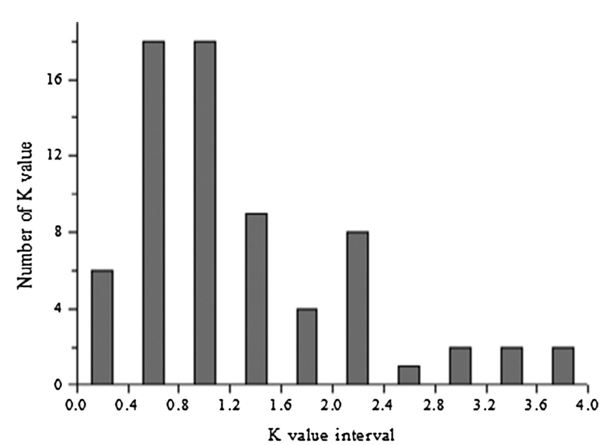
Eqn (2) indicates that the *K*-factor stands for the actual dose rate to caregivers for the reference dose during the period of care. The reference dose is the accumulated dose at 1 m from the patient until most of the radioactivity inside the patient is spent, while the dose of the caregiver (H_c) is the actual exposure generated during care of the patient. Therefore, factor *K* plays the role of an index of the degree of engagement between caregivers and patients. Accordingly, herein factor *K* is called the engagement factor.

All the factors on the right side of eqn (7) have known values except the caregiver dose H_c. Therefore, it is possible to calculate the engagement factor between caregiver and patient when substituting the measured caregiver dose.

Fig. 7 illustrates the summary of frequency distribution and statistical data for the value of the engagement factor *K* calculated using eqn (7). As shown in this figure, the *K* value is distributed over a relatively large range between 0.31 and 3.9, and the trend is biased to lower values similar to the dose distribution of caregivers seen in Fig. 2. The arithmetic mean and standard deviation of the K value are 1.3 and 0.88, respectively; the geometric mean and its standard deviation are 1.0 and 2.1, respectively. The median is 1.0. One finds the arithmetic standard deviation to be significantly smaller than the geometric standard deviation. Using the mean value of *K*, 1.3, the total external dose to a caregiver can be estimated as $1.1 \times Q_0 \times e^{-0.05Tr}$ mSv.

CONCLUSION

The dose of external radiation passed from patients to caregivers varied according to behavioral patterns of each patient/caregiver pair. The authors made use of passive thermoluminescence dosimeters to measure the doses received by 70 primary caregivers from patients administered high activity radioiodine ^{131}I after thyroidectomies. The purpose was to assess the actual caregiver radiation dose. The patients were kept in isolation wards for 3–4 d after the administration of 1.22 GBq before being released from the hospital. The effective average caregiver dose, resulting from external radiation exposure from patients after their release from the hospital, was assessed to be 0.12 ± 0.10 mSv. This value is equivalent to 2.5% of the dose limit of 5 mSv recommended by ICRP for caregivers, and it has been assumed that caregivers and patients maintained faithful compliance with the behavioral guidelines provided by hospital staff after patients left the hospital. From these results, the approximate personal dose exposed to typical caregivers after patients administered Q_0 GBq of ^{131}I were released from the hospital can be calculated at $0.86 \times K \times Q_0 \times e^{-0.05Tr}$ mSv. The variable T_r is the time the patient leaves the hospital, and *K* is a dimensionless factor relevant to the degree of contact between patients and caregivers, equivalent to 1.3 ± 0.88, which is called the engagement factor herein. This prediction model or approach is applicable to both caregivers of patients



Arithmetic mean (SD)	Geometric mean (GSD)	Median	Maximum Minimum
1.3 (0.88)	1.0 (2.1)	1.0	3.8 0.31

Fig. 7. Frequency distribution of engagement factor K (SD: standard deviation. GSD: geometric standard deviation).

and medical staff members in cases involving use of radioiodine.

This model may be widened to include the use of other types of radionuclide. It will be possible from the predictive model to calculate an adequate number of days of hospitalization for patients to increase the safety to others, if the doses to persons in the vicinity of patients after their release can be measured, to set up the model. Assessing the current hospitalization practices of thyroid cancer patients based on the model developed in this study indicates that the current hospitalization interval of three days and two nights is sufficiently conservative with respect to compliance with the ICRP recommendation. Therefore, a good focus for future work will be to search for measures to reduce the hospitalization period of patients administered relatively lower ^{131}I levels of activity by applying different hospitalization periods based upon dosage administered to patients. Exposure of caregivers after the patient is released from the hospital is maximized in the first 1 or 2 d, including the initial travel time home from the hospital. Exposure to caregivers might be reduced to a sufficient degree by developing tools and guidelines for protection from radiation aimed at minimizing internal and external exposure during the period of maximal dosage, and by enhancing or supplementing the current education and precautions provided for patients and caregivers.

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