INTERNATIONAL STANDARD

**ISO 18310-1**

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# Measurement and prediction of the ambient dose equivalent from patients receiving iodine 131 administration after thyroid ablation —

## Part 1:
## During the hospitalization

*Mesurage et prévision de l'équivalent de dose ambiant de patients bénéficiant d'un traitement par iode 131 après ablation de la thyroïde —*

*Partie 1: Pendant l'hospitalisation*

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# Foreword

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The committee responsible for this document ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

A list of all the parts in the ISO 18310 series can be found on the ISO website.

# Introduction

ISO 18310 addresses measurement methods and procedures of ambient dose equivalent rate from patients administered with $^{131}$I.

The incidence of thyroid cancer has increased in recent years. Thyroid cancer can be treated by administering radioiodine, because radioiodine selectively accumulates in thyroid tissue to irradiate and kill the cancerous cells. Thyroid cancers are small and not likely to develop into aggressive malignancies. Earlier diagnosis and treatment can remove these cancers at a time when they are not likely to have spread beyond the thyroid gland.

However, due to the radiation emitted from patients during treatment, the patients nearby or the caregivers could also receive the dose. For this reason, a normative way to assess the dose to persons close to the patient treated with radioiodine should be implemented. There are two common practices for the treatment of thyroid cancer, one is a radioiodine administration without thyroid resection, and the other is the administration after thyroid resection. In recent years, the radioiodine administration after surgery has become more common.

The most commonly used radionuclides for the treatment is $^{131}$I. $^{131}$I mainly emits 364 keV of photon energy with a few other photons and its radiological half-life is 8,02 d. The administered iodine is absorbed in the digestive system, concentrated in the thyroid gland through blood circulation and after a few hours, excreted into the bladder, and released through urine and faeces. For the patient who had the thyroid removed, the retention time in the body is shorter than that for a patient who has not had thyroid removal.

This document deals with the determination of ambient dose equivalent rate at a distance from the patient treated with radioiodine therapy procedure. It is based on the estimation of the dose rate using ionization chamber base dosimetry.

For the purpose of the ISO 18310 series, this document is focused on the determination of the ambient dose equivalent rate from the patient. The uncertainty of the ambient dose equivalent is also provided.

# Measurement and prediction of the ambient dose equivalent from patients receiving iodine 131 administration after thyroid ablation —

# Part 1:
# During the hospitalization

## 1 Scope

This document specifies suitable methods for the measurement of ambient dose equivalent rate at a distance from the patient treated with radioiodine to ablate the thyroid. For this purpose, direct measurement of the ambient dose equivalent rate due to the inpatients using an ionization chamber (or other suitable devices) may be employed.

This document addresses the measurement methods, the calibration of ionization chamber and the uncertainty estimation for the measurement of the ambient dose equivalent rate of the patient treated with radioiodine to ablate the thyroid using the ionization chamber.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 4037-1, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 1: Radiation characteristics and production methods*

ISO 4037-3:1999, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 3: Calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence*

ISO 29661, *Reference radiation fields for radiation protection — Definitions and fundamental concepts*

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions given in ISO 4037 series, ISO/IEC Guide 99, ISO 29661 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

**3.1**
**radioiodine**
iodine-131 ($^{131}$I) decays with a half-life of 8,02 d with beta and gamma emissions

Note 1 to entry: On decaying, $^{131}$I most often (89 % of the time) expend 971 keV of decay energy by transforming into stable $^{131}$Xe in two steps with gamma decay following rapidly after beta decay. The primary emissions of $^{131}$I decay are beta particles with maximum energy of 606 keV and 364 keV gamma rays. Major application of $^{131}$I is for the direct radioisotope therapy to treat hyperthyroidism and some types of thyroid cancer.

**3.2**
**air kerma**
sum of the initial kinetic energies of all the charged particles liberated by uncharged ionizing radiation, such as photons and neutrons in air, divided by the mass of air

**3.3**
**ambient dose equivalent *H**(10)**
dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned ICRU sphere positioned at a depth of 10 mm along the central axis of the aligned field

**3.4**
**ionization chamber**
simplest type of all gas-filled radiation detectors that is widely used for the detection and measurement of certain types of ionizing radiation (X-rays, gamma-ray~~s~~ and beta particles) that collects all the charges created by direct ionization within the gas through the application of an electric field without amplification of the liberated electrons

**3.5**
**calibration**
operation under specified conditions that, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

**3.6**
**standard calibration system**
calibration system used to establish a reference condition for the *calibration* (3.5)

Note 1 to entry: It includes the reference instrument (reference ionization chamber with measurement unit of current or charge and ambient conditions such as temperature and pressure) and the standard irradiation system.

**3.7**
**instrument to be calibrated**
instrument provided by the client to the standard laboratory for calibration services

**3.8**
**air kerma of reference**
*air kerma* (3.2) determined by the *standard calibration system* (3.6)

**3.9**
**reference irradiation system**
irradiator unit to establish the *reference air kerma* (3.8) rate for gamma-ray or X-ray

**3.10**
**reference irradiation method**
method of obtaining a *calibration coefficient* (3.14) of an instrument by comparing the readout of the instrument with *air kerma* (3.2) rate at the calibration point determined by *reference irradiation system* (3.9)

**3.11**
**beam size**
area of the irradiation beam within which the radiation dose rate is greater than 50 % of the maximum value at the centre of the area on the reference plane located at 1 m from the source

Note 1 to entry: This term is usually defined as FWHM (full width half maximum).

**3.12**
**effective beam size**
effective area of the irradiation beam within which the radiation dose rate is greater than 95 % of the maximum value at the centre axis of the area on the reference plane located at 1 m distance from the source

Note 1 to entry: In this area, radial non-uniformity correction becomes negligible.

**3.13**
**standard ambient condition**
standard values of temperature and pressure (20 °C, 101,325 kPa) to which the dose rates of the dosimeters measured in the laboratory are corrected

**3.14**
**calibration coefficient**
factor which converts of the conventional true value of the quantity the instrument is intended to measure divided by the indication of the instrument, corrected to *standard ambient condition* (3.13)

Note 1 to entry: For example, the calibration coefficient $N$ with respect to ambient dose equivalent measured by *ionization chamber* (3.4) is given by $N = H^*(10)/M$, where $M$ is a dosimetric reading at the reference point of the ionization chamber.

**3.15**
**radiation field non-uniformity correction**
conversion between the dose rate at a certain point in the radiation field and the measured average dose rate over the volume of the cavity of the detector

# 4 Measurement of ambient dose equivalent

## 4.1 General

Measurement of ambient dose equivalent rate from a patient treated with radioiodine administration is done using an ionization chamber as detailed below.

## 4.2 Calibration of the ionization chamber in the reference radiation

The calibration procedure of the ionization chamber with respect to ambient dose equivalent by the national standard laboratory or the accredited laboratory is as follows.

The ionization chamber is calibrated using either the substitution method or the reference radiation method. In the substitution method, the measurement using the reference ion chamber and the one to be calibrated is performed at the same position with the exchange of the chambers. The calibration coefficient is then determined from the ratio of two measured values. On the other hand, the ion chamber calibration coefficient can be obtained by positioning it in the reference radiation field in which the dose rate of each position was already determined by the calibration of the radiation field.

a) The user should be trained and competent in the facility's calibration procedure prior to calibrating an ion chamber.

b) Make sure that the ionization chamber to be calibrated is in proper working condition.

c) Confirm that the centre point of the chamber is on the central axis of the beam. The central axis of the chamber stem is perpendicular to the direction of the beam and the marker or inscription on the neck of the chamber faces the radiation source.

d) Determine that the beam size is greater than the size of the sensitive volume of the chamber by a factor of 1,5 to 2.

e) Place the chamber at the calibration point and stabilize it after applying an appropriate voltage through the measuring assembly.

f) Measure the leakage current or charge of the chamber at least five times before irradiation for calibration purpose.

g) Establish and maintain environmental conditions for the calibration at 23 °C ± 2 °C, and at 50 % ± 20 % relative humidity during the measurement.

h) Upon irradiation from the standard irradiation system, measure the current or charge of the chamber more than five times.

i) If the difference is more than ±0,3 % between the initial and final current measurements or more than ±0,2 % in the atmospheric correction factor during the calibration, repeat steps f), g) and h).

j) Configuration of the irradiation system and the ionization chamber shall be arranged in accordance with the condition in Figure 1.

k) Ambient dose equivalent for the reference radiations ($^{137}$Cs or $^{60}$Co) are obtained by multiplying the conversion coefficient $h_{\mathrm{K}}^{*}\left(10\right)$ by the air kerma using the ionization chamber. Conversion coefficients from air kerma to ambient dose equivalent $H^{*}\left(10\right)$ for mono-energetic and parallel photon radiation (expanded and aligned) and the ICRU sphere is given in ISO 4037-3:1999, Table 8 and the conversion coefficients $h_{\mathrm{K}}^{*}\left(10;S\right)$ from air kerma to ambient dose equivalent for radiation qualities of radionuclides is given in ISO 4037-3:1999, Table 8.

## 4.3 Measurement of ambient dose equivalent

Measurement of the ambient dose equivalents for $^{131}$I using the ionization chamber during the clinical experiments is as follows**.**

a) During hospitalization, at certain times after the radioiodine administration, the patient shall be instructed to participate in the measurement of the current using the ionization chamber by positioning the chamber 10 cm away from the neck of the patient and 1 m away from the patient.

b) Ambient dose equivalent due to $^{131}$I can be determined by multiplying the ambient dose equivalent for the reference radiation by the ratio of the conversion coefficients between $^{131}$I and the reference radiation. The conversion coefficient for $^{131}$I can be deduced as follows.

    1) From ISO 4037-3:1999, Table 8 of the conversion coefficients $h_{\mathrm{K}}^{*}\left(10;S\right)$ from air kerma to dose equivalent $H^{*}\left(10\right)$ in the ICRU sphere for the mono-energetic photon radiation, the graph between the photon energy versus conversion coefficient can be plotted.

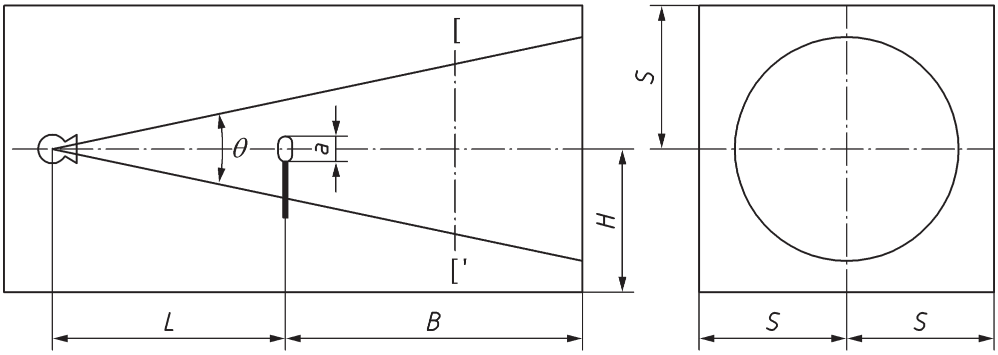
    2) For the energy range of 10 keV to 10 MeV, each data point can be fit to the formula $h_{\mathrm{K}}^{*}(x) = a + b / x + c / x^{2} + d / x^{3} + e / x^{4} + f / x^{5} + g / x^{6}$ and thus, from the interpolation, the conversion coefficient for the gamma radiation with energy of 364 keV liberated from $^{131}$I can be determined as 1,27. This fit function doesn't have a physical meaning, but in this energy range, the conversion coefficients for the radioisotopes whose values were given in the ISO 4037-3, give good matches with each other.

3) The graph is given in Figure 2 and the uncertainty of the interpolation method can be estimated from the relation, in per cent (%):

$$\sqrt{\frac{\sum\left[100\times\left(h_{\mathrm{K}}^{*\mathrm{ISO}}-h_{\mathrm{K}}^{*\mathrm{cal}}\right)\Big/h_{\mathrm{K}}^{*\mathrm{ISO}}\right]^{2}}{N-m}}$$

where

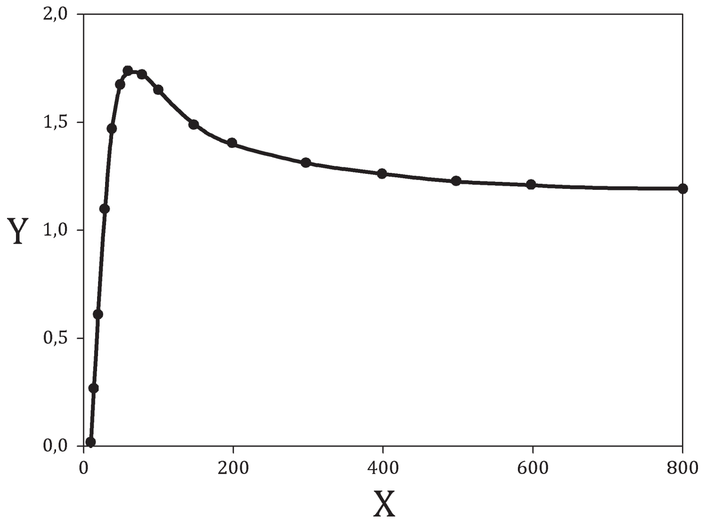
| | |
|---|---|
| $h_{\mathrm{K}}^{*\mathrm{ISO}}$ | is the reference value from ISO 4037-3; |
| $h_{\mathrm{K}}^{*\mathrm{cal}}$ | is the value obtained from the fit function; |
| $N$ | is the number of calculation; |
| $m$ | is the number of parameters in the fit function. |



**Key**

| | |
|---|---|
| $L$ | source to instrument distance ($L > 0{,}5$ m) |
| $a$ | size of the detecting unit of the instrument ($a/L < 1/5$) |
| $B$ | instrument to back wall distance ($B > 1{,}5$ m) |
| $H$ | distance from the central axis of the beam to the floor ($H > 1{,}0$ m) |
| $S$ | distance from the central axis of the beam to either side wall or ceiling ($S > 1{,}5$ m) |
| $\theta$ | angular distribution of the irradiated beam ($\theta < 40°$) |

**Figure 1 — Geometrical configuration of the reference gamma irradiator and the instrument**



**Key**

X mono-energetic radiation beam (KeV)

Y conversion coefficient

**Figure 2 — Plot of conversion coefficient from air kerma to the ambient dose equivalent in the ICRU sphere as a function of photon energy (referenced from ISO 4037-3)**

## 4.4 Examination of uncertainty elements

Examine the uncertainty elements involved in the measurement and estimate the total combined uncertainty of the ambient dose equivalent from the mathematical model of the uncertainty calculation. The uncertainty of the calibration coefficient of ionization chamber is provided from the calibration certificate and it is a systematic uncertainty (type B). This uncertainty comprises the uncertainty components of the reference calibration conditions such as the current measurement, reference air kerma rate, positioning of the ionization chamber, the correction to the standard ambient conditions, radiation field non-uniformity and conversion coefficients from air kerma to dose equivalent in the reference radiation ($^{137}$Cs or $^{60}$Co gamma-rays). Other uncertainty elements are the uncertainty of current measurement (statistical uncertainty, type A), the uncertainty of correction of ambient conditions (type B), the uncertainty of positioning the ionization chamber in $^{131}$I radiation (type B) and the uncertainty of the ratio of the conversion coefficients between $^{131}$I and the reference radiations (type B).

# 5 Mathematical model for a calibration of ionization chamber

## 5.1 General

The mathematical model for the calibration of ionization chambers with respect to ambient dose equivalents in the reference radiation and measurement of ambient dose equivalents in $^{131}$I is as follows.

### 5.2 Calibration coefficient of an ionization chamber in the reference radiation

For the calibration of ionization chamber with respect to ambient dose equivalents from air kerma, the calibration coefficient of the chamber can be obtained using Formula (1):

$$N_{\mathrm{r}} = \frac{\dot{K}_{\mathrm{a}} \cdot h_{\mathrm{K}}^{*\mathrm{ref}}}{I_{\mathrm{r}} \cdot k_{\mathrm{tp}}} \tag{1}$$

where

$N_{\mathrm{r}}$ is the calibration coefficient of the ionization chamber;

$\dot{K}_{\mathrm{a}}$ is the air kerma of reference rate;

$h_{\mathrm{K}}^{*\mathrm{ref}}$ is the conversion coefficient from air kerma to dose equivalent in the reference radiation;

$I_{\mathrm{r}}$ is the measurement of the current in the reference radiation;

$k_{\mathrm{tp}}$ is the correction factor of ambient conditions (temperature and pressure) during the calibration; it is only used for open ionisation chamber. The current or charge measured by the chamber is normalized to the reference conditions 20 °C and 101,325 kPa:

$$k_{\mathrm{tp}} = \frac{273{,}15 + T}{273{,}15 + T_0} \cdot \frac{P_0}{P} \tag{2}$$

where

$T_0$ is the reference temperature (20 °C);

$T$ is the temperature measured during calibration;

$P_0$ is the reference pressure (101,325 kPa);

$P$ is the pressure measured during calibration.

### 5.3 Measurement of ambient dose equivalent rate using a calibrated ionization chamber in an $^{131}$I radiation field

$$H^{*}(10) = I_{\mathrm{u}} \cdot N_{\mathrm{r}} \cdot k_{\mathrm{tpu}} \cdot r \tag{3}$$

where

$H^{*}(10)$ is the ambient dose equivalent for $^{131}$I;

$I_{\mathrm{u}}$ is the measurement of the current for $^{131}$I;

$N_{\mathrm{r}}$ is the calibration coefficient of the ionization chamber;

$k_{\mathrm{tpu}}$ is the correction factor of ambient conditions (temperature and pressure) for $^{131}$I;

$r = \dfrac{h_{\mathrm{K}}^{*131\mathrm{I}}}{h_{\mathrm{K}}^{*\mathrm{ref}}}$ is the ratio of the conversion coefficients between $^{131}$I and the reference radiation.

## 6 Quality control

The ion chamber shall be calibrated to air kerma periodically by either a national laboratory or an accredited laboratory. As per Bureau International des Poids et Mesures (BIPM) report, stability of the calibration coefficient of the chamber shall be maintained within 1,5 %. The ionization chamber + the cable + the electrometer shall be calibrated as a unit. The thermometer, barometer and hygrometer shall also be calibrated periodically by the relevant accredited laboratory.

## 7 Uncertainty budget and estimation of uncertainty

### 7.1 Relative combined standard uncertainty

According to the uncertainty propagation law, relative combined standard uncertainty is given as a square root of sum of the square of every uncertainty factor under consideration. Since the uncertainty element for different calibration set ups may vary from one another and also consists of the combination of multiplication and division of several quantities, the sensitivity of each component should be included in the estimation of the combined uncertainty.

Sensitivity coefficient: all 1,0 because the quantities shown in the formula are independent of each other.

The uncertainty equation for the calibration coefficient of the ionization chamber calibrated in the reference radiation is as given in Formula (4):

$$u_C\left(N_{\mathrm{r}}\right)=\sqrt{u^2\left(\dot{K}_{\mathrm{a}}\right)+u^2\left(I_{\mathrm{r}}\right)+u^2\left(k_{\mathrm{E}}\right)+u^2\left(k_{\mathrm{tp}}\right)+u^2\left(k_{\mathrm{d}}\right)+u^2\left(k_{\mathrm{nu}}\right)+u^2\left(h_{\mathrm{K}}^{*\mathrm{ref}}\right)} \tag{4}$$

where

$u\left(\dot{K}_{\mathrm{a}}\right)$ is the uncertainty of the air kerma of reference rate;

$u(I_{\mathrm{r}})$ is the uncertainty of measurement of the current or charge in the reference radiation;

$u(K_{\mathrm{E}})$ is the uncertainty of the current measurement unit;

$u(k_{\mathrm{tp}})$ is the uncertainty of correction factor of ambient conditions in the reference radiation;

$u(k_{\mathrm{d}})$ is the uncertainty of positioning of the chamber;

$u(k_{\mathrm{nu}})$ is the uncertainty of radiation field non-uniformity correction;

$u\left(h_k^{*ref}\right)$ is the uncertainty of conversion coefficient from air kerma to dose equivalent in the reference radiation.

The calibration coefficient of the ionization chamber with the expanded uncertainty is shown in the calibration certificate issued by the standard calibration laboratory. The results of detailed uncertainty estimation can be obtained upon request.

The uncertainty formula for the measurement of ambient dose equivalent using the calibrated ionization chamber in $^{131}$I is as given in Formula (5):

$$u_{\mathrm{C}}\left[H^*(10)\right]=\sqrt{u^2\left(N_{\mathrm{r}}\right)+u^2\left(I_{\mathrm{u}}\right)+u^2\left(k_{\mathrm{tpu}}\right)+u^2\left(k_{\mathrm{d}}\right)+u^2(r)} \tag{5}$$

where

$u(N_r)$ is the uncertainty of calibration coefficient of the ionization chamber;

$u(I_u)$ is the uncertainty of measurement of the current for $^{131}$I;

$u(k_{tpu})$ is the uncertainty of correction factor of ambient conditions for $^{131}$I;

$u(k_d)$ is the uncertainty of positioning of the chamber for $^{131}$I;

$u(r)$ is the uncertainty of the ratio of the conversion coefficients between $^{131}$I obtained from the interpolation of photon energy versus conversion coefficient fit function and the reference radiation.

## 7.2 Relative combined standard uncertainty of $u_C$ [$H^*(10)$]

The details of the various physical parameters expected to contribute in combined standard uncertainty of ambient dose equivalents due to the patient is given in Table 1.

## 7.3 Expanded uncertainty

Effective degree of freedom should be determined to obtain the expanded standard uncertainty, which can be done using the Welch–Salterthwaite formula given in Formula (6) according to the method recommended in Reference [6].

$$\nu_{\text{eff}} = \frac{u_C{}^4(y)}{\sum \frac{u_i^4}{\nu_i}} \tag{6}$$

Coverage factor $k$ is determined by the level of confidence and effective degree of freedom and is dependent upon the confidence interval in t-distribution. When the effective degree of freedom becomes infinite, $k = 2$ in the 95,45 % level of confidence and the expanded standard uncertainty is given as Formula (7):

$$U\left[H^*\left(10\right)\right] = k \cdot u_c\left[H^*\left(10\right)\right] = 2\,u_c\left[H^*\left(10\right)\right] \tag{7}$$

**Table 1 — Relative combined standard uncertainty of**

| Uncertainty element | Type of uncertainty | Probability distribution | Coverage factor | Degree of freedom |
|---|---|---|---|---|
| Uncertainty of calibration coefficient of ionization chamber calibrated in the reference radiation, $u\left(N_r\right)$ | B | t | 1/2 | ∞ |
| Uncertainty of the air kerma of reference rate, $u\left(\dot{K}_a\right)$ | B | N | 1/2 | ∞ |
| Uncertainty of measurement of the current in the reference radiation, $u\left(I_r\right)$ | A | t | t | 4 |
| Uncertainty of current measurement unit, $u\left(K_E\right)$ | B | rectangular | $1/\sqrt{3}$ | ∞ |
| Uncertainty of correction factor of ambient conditions in the reference radiation, $u\left(k_{tp}\right)$ | B | t | 1/2 | ∞ |

**Table 1** *(continued)*

| Uncertainty element | Type of uncertainty | Probability distribution | Coverage factor | Degree of freedom |
|---|---|---|---|---|
| Uncertainty of positioning of the ionization chamber in the reference radiation field, $u\left(k_{\mathrm{d}}\right)$ | B | rectangular | $1/\sqrt{3}$ | ∞ |
| Uncertainty of radiation field non-uniformity correction, $u\left(k_{\mathrm{nu}}\right)$ | B | rectangular | $1/\sqrt{3}$ | ∞ |
| Uncertainty of conversion coefficient from air kerma to dose equivalent in the reference radiation, $u\left(h_{\mathrm{K}}^{*\mathrm{ref}}\right)$ | B | N | 1,0 | ∞ |
| Uncertainty of measurement of the current for $^{131}\mathrm{I}$, $u\left(I_{\mathrm{u}}\right)$ | A | t | 1,0 | 4 |
| Uncertainty of correction factor of ambient conditions for $^{131}\mathrm{I}$, $u\left(k_{\mathrm{tpu}}\right)$ | B | t | 1/2 | ∞ |
| Uncertainty of positioning of the chamber for $^{131}\mathrm{I}$, $u\left(k_{\mathrm{d}}\right)$ | B | rectangular | $1/\sqrt{3}$ | ∞ |
| Uncertainty of the ratio of the conversion coefficients between $^{131}\mathrm{I}$ obtained from interpolation method and the reference radiation, $u\left(r\right)$ | B | N | 1,0 | ∞ |
| Total combined uncertainty, $u_{\mathrm{C}}\left[H^{*}\left(10\right)\right]$ | | | | |
| Extended uncertainty $U\left[H^{*}\left(10\right)\right]=k\cdot u_{\mathrm{c}}\left[H^{*}\left(10\right)\right]=2u_{\mathrm{c}}\left[H^{*}\left(10\right)\right]$ | | | | |

# Annex A
(informative)

# Experimental application to this document: measurement and prediction of the ambient dose equivalent rate from patients receiving radioiodine 131 administration after thyroid ablation

## A.1 General

This document aims at measuring ambient dose equivalents rate at a distance from the body of the patients who received $^{131}$I after thyroid resection due to the gamma radiation emitted from $^{131}$I.

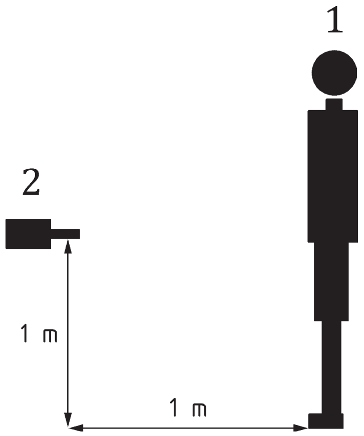
The ambient dose equivalent rates from the patients receiving high-dose $^{131}$I treatment to ablate the thyroid were measured using ionization chamber. Total ambient dose equivalent at a certain period of time can be calculated as an integral of the measurement curve during that time period. Based on the experimental data, the prediction equations at 1 m away from the chest of patient were proposed with the administered activity. The effective half-life for the patients was estimated to 13,9 h.

To evaluate the ambient dose equivalent rates around patient and the corresponding retention, from the radioiodine administration using a traditional thyroid hormone withdrawal protocol, several studies have been performed. Reference [1] measured the dose rates for two groups of patients, the ablation group and the follow-up group. The definitions of two groups were cited from Reference [1]. The measured dose rate decayed bi-exponentially for the ablation group and mono-exponentially for the follow-up group. In this study, they standardized measurement methods allowing the measurement of a certain distance and upright appearance with various levels of the patients ingesting the radioactive iodine. Reference [2] evaluated the effective half-life by measuring the external dose rates of the patients. They suggested 14 h as a median effective half-life. Reference [3] also suggested 11,41 h ± 0,02 h for the effective half-life.

## A.2 Summary of measurement

Depending on the seriousness of the symptoms, data for the 59 patients treated with high activity $^{131}$I ranging from 3,70 GBq to 7,40 GBq (from 100 mCi to 200 mCi) after thyroid resection have been used for this study. Among the 59 patients, 4 patients were treated with 3,70 GBq, 44 patients with 5,55 GBq, 6 patients with 6,66 GBq and 4 patients with 7,40 GBq. The treatment was done following a traditional thyroid hormone withdrawal protocol. During hospitalization, at 1 h, 2 h, 4 h, 17 h, 19 h, 23 h, 26 h and 48 h after the radioiodine administration, the patient participated in the measurement using an OD-01HxE ionization chamber (STEP, Germany) both at 10 cm from his neck and 1 m away from his position. The patients were explained the details of the contents of Institutional Review of Board (IRB) of Kyungbuk National University Hospital and signed in the written consent about their participation to the measurement. The number of measurements was two. The calibration of the detector was performed in one of the accredited laboratories in Korea, and the calibration uncertainty was within 5 % for the detector.

Measurements were performed in a fixed position in front of the patient room door. At 4 h after administration, the patients went to bed and the measurement was postponed in order to not disturb their sleep, which was the reason for the longer time interval of between 4 h and 17 h after administration. Measurements were carried out by the department of nuclear medicine of Kyungpook National University Hospital for two months in the summer 2010 by a radiation safety officer (RSO). Background was measured and subtracted at the measurement location. Background readings were, on average, 1,39 $\mu\text{Gy}\cdot\text{h}^{-1}$ and the standard deviation was 0,775 $\mu\text{Gy}\cdot\text{h}^{-1}$. Patient position and distance for the detector's measurement are shown in Figure A.1. The measurement results for the standard dose rate 1 m away from the body of the patient after radioiodine administration are shown in Table A.3.



**Key**

1 patient

2 detector

Figure A.1 — Detector and patient position

## A.3 Result

For the patients treated with $^{131}$I to ablate the thyroid, the measurement of ambient dose equivalent rate was performed both at the position 10 cm away from the neck of the patient and at a distance of 1 m away from the patient. Since the activity of $^{131}$I administered to the patient was different depending on the patient's clinical symptom, the unit of measurement was obtained as µSv·h$^{-1}$ per MBq of administered activity by dividing ambient dose equivalents rate of each patient by the total administered activity to him.

The measurement results with a detector for the same patient are shown in Table A.1.

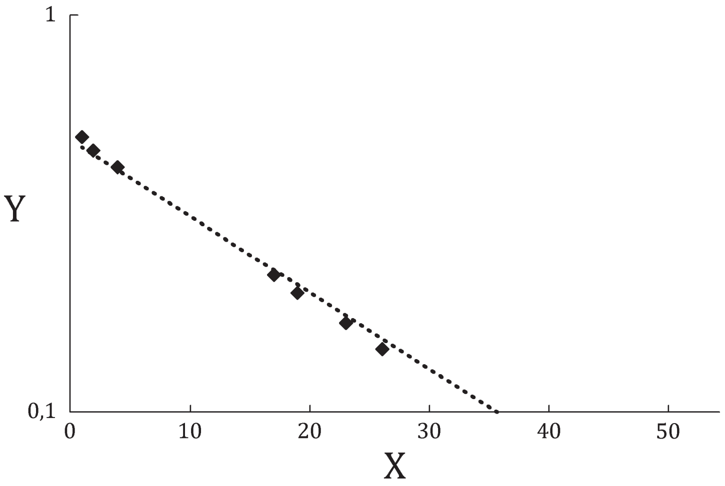
Table A.1 — Dose rate from follow-up patients (µSv·h$^{-1}$ per MBq of administered activity)

| Distance | Hours | 1 | 2 | 4 | 17 | 19 | 23 | 26 | 48 |
|---|---|---|---|---|---|---|---|---|---|
| | **Administered activity** | 3,70 GBq ; 5,55 GBq ; 6,66 GBq ; 7,40 GBq | | | | | | | |
| 10 cm from neck | Mean | 0, 610 4 | 0,566 9 | 0,517 8 | 0,269 2 | 0,244 6 | 0,202 2 | 0,173 9 | 0,076 6 |
| | Standard deviation | 0,068 9 | 0,047 0 | 0,042 8 | 0,071 4 | 0,060 6 | 0,058 6 | 0,052 8 | 0,038 0 |
| | Sample number | 59 | 59 | 59 | 57 | 56 | 58 | 59 | 19 |
| | *k* = 2 in 95,45 % level of confidence | 0,615 7 | 0,538 5 | 0,491 5 | 0,352 0 | 0,311 5 | 0,274 2 | 0,240 3 | 0,135 0 |
| 1 m from patient | Mean | 0,050 8 | 0,047 0 | 0,041 9 | 0,024 5 | 0,021 3 | 0,017 3 | 0,012 8 | 0,004 8 |
| | Standard deviation | 0,005 5 | 0,005 3 | 0,004 9 | 0,007 3 | 0,005 5 | 0,006 0 | 0,004 2 | 0,002 2 |
| | Sample number | 59 | 59 | 59 | 57 | 56 | 58 | 59 | 19 |
| | *k* = 2 in 95,45 % level of confidence | 0,050 8 | 0,047 1 | 0,042 7 | 0,033 7 | 0,027 7 | 0,025 5 | 0,018 3 | 0,008 0 |

The measurement results of the dose rate for 44 patients treated with 5,55 GBq of $^{131}I$ using the ionization chamber are shown in Table A.2 and the change of dose rate as a function of time are given in Figure A.2 and Figure A.3.

**Table A.2 — Dose rate measurements for patients treated with 5,55 GBq (150 mCi)**

| **Time** (hours) | **10 cm from neck** ($\mu Sv \cdot h^{-1}$ per MBq of administered activity) | **1 m from patient** ($\mu Sv \cdot h^{-1}$ per MBq of administered activity) |
|---|---|---|
| 1 | 0,623 2 | 0,051 4 |
| 2 | 0,572 1 | 0,047 5 |
| 4 | 0,524 8 | 0,042 5 |
| 17 | 0,278 9 | 0,025 7 |
| 19 | 0,252 7 | 0,022 1 |
| 23 | 0,213 2 | 0,018 8 |
| 26 | 0,182 8 | 0,014 |
| 48 | 0,079 6 | 0,005 |

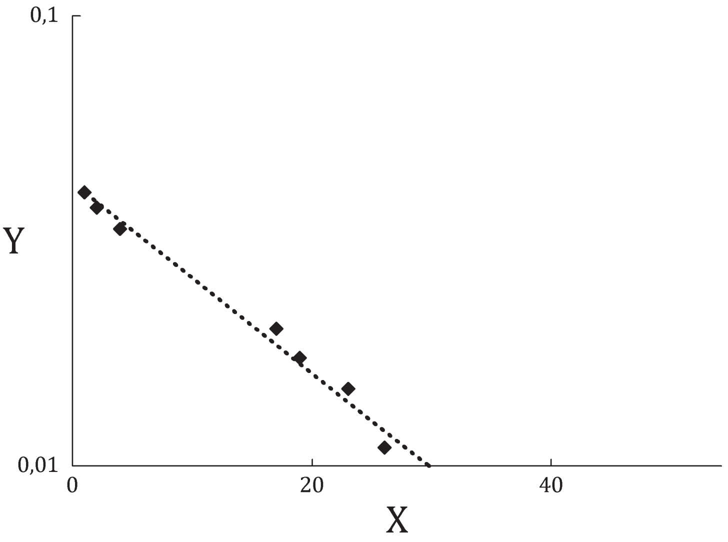


**Key**

X time (h)

Y dose rate (µSv/h) per MBq

Figure A.2 — Measurement results of the dose rate as a function of time at 10 cm away from the neck of the patient



**Key**

X time (h)

Y dose rate (μSv/h) per MBq

**Figure A.3 — Measurement results of the dose rate as a function of time at 1 m away from the body of the patient**

Based on the exponential fit with a simple regression analysis for the dose rate measured by the ionization chamber with 95,45 % in the level of confidence, the basic formula for determining the external dose rate from the patient can be calculated as follows:

a) Dose rate at 1 m away from the whole body of the patient treated with 5,55 GBq (see Figure A.4).

The formula derived from the regression analysis is as follows:

$y = 0{,}235\,8e^{-0{,}050\,1\cdot t}$ [mGy/h], for 5,55 GBq intake

$R^2$ = 0,9939, effective half-life = 13,9 h

where

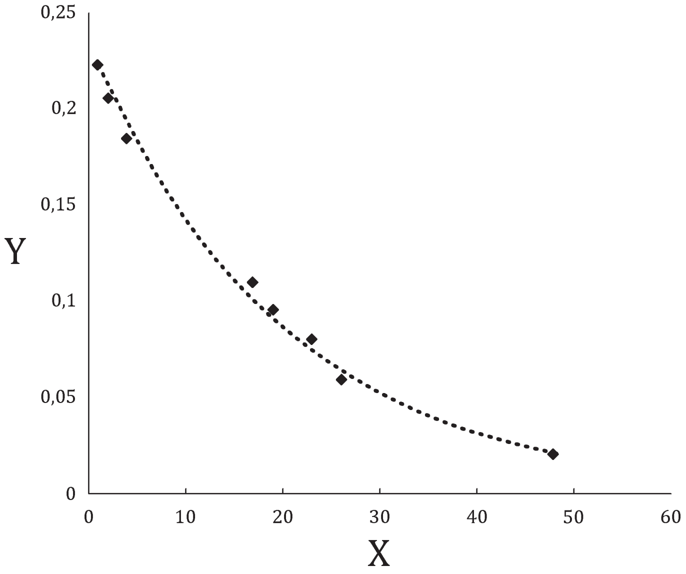
$t$ is the elapsed time after ingestion of radioactive iodine (h).

The coefficient of determination of this regression analysis is 0,903, standard error is 0,024. Significant $F$ value of 2,96 × $10^{-4}$, $P$-values for the y-intercept is 6,17 × $10^{-6}$. The distribution of standard residuals are 1,10, approximately 1,48.

Since the intake of $^{131}$I is 5,55 GBq, the dose rate at the time $t$ ($DR_{\text{Body}}$) can be expressed as Formula (A.1).

$$DR_{\text{Body}} = 4{,}287 \times 10^{-2}\, C_0\, e^{-0{,}050\,1\cdot t} \left[\text{mGy} \cdot \text{h}^{-1}\right] \qquad \text{(A.1)}$$

where $C_0$ is the $^{131}$I initial uptake [GBq].



**Key**

X time (h)

Y dose rate (μSv/h) per MBq

**Figure A.4 — Dose rate as a function of time at 1 m away from the body of the patient**

b) Dose rate at 10 cm from the neck of the patient treated with 5,55 GBq (see Figure A.5).

The formula derived from the regression analysis at 10 cm from neck was as follows:

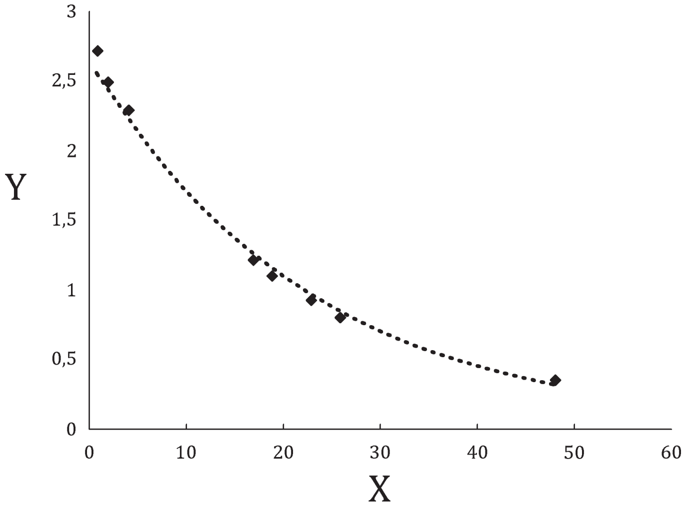
$y = 2{,}675\,9e^{-0{,}044\,3\cdot t}$ [mGy/h], for 5,55 GBq intake

$R^2$ = 0,9943, effective half-life = 15,6 h

The coefficient of determination is 0,087, where the standard error is 0,344. Significant *F* value of $7{,}01\times10^{-4}$, *P*-values for the y-intercept is $1{,}42\times10^{-5}$. The distribution of standard residuals are 0,96, approximately 1,46.

Similarly, the dose rate with time t at 10 cm from neck ($\mathrm{DR_{Thyroid}}$) also can be expressed as given in Formula (A.2):

$$DR_{\mathrm{Thyroid}} = 4{,}865\times10^{-1}\,C_0\,e^{-0{,}044\,3\cdot t}\left[\mathrm{mGy}\cdot\mathrm{h}^{-1}\right] \qquad \text{(A.2)}$$



**Key**

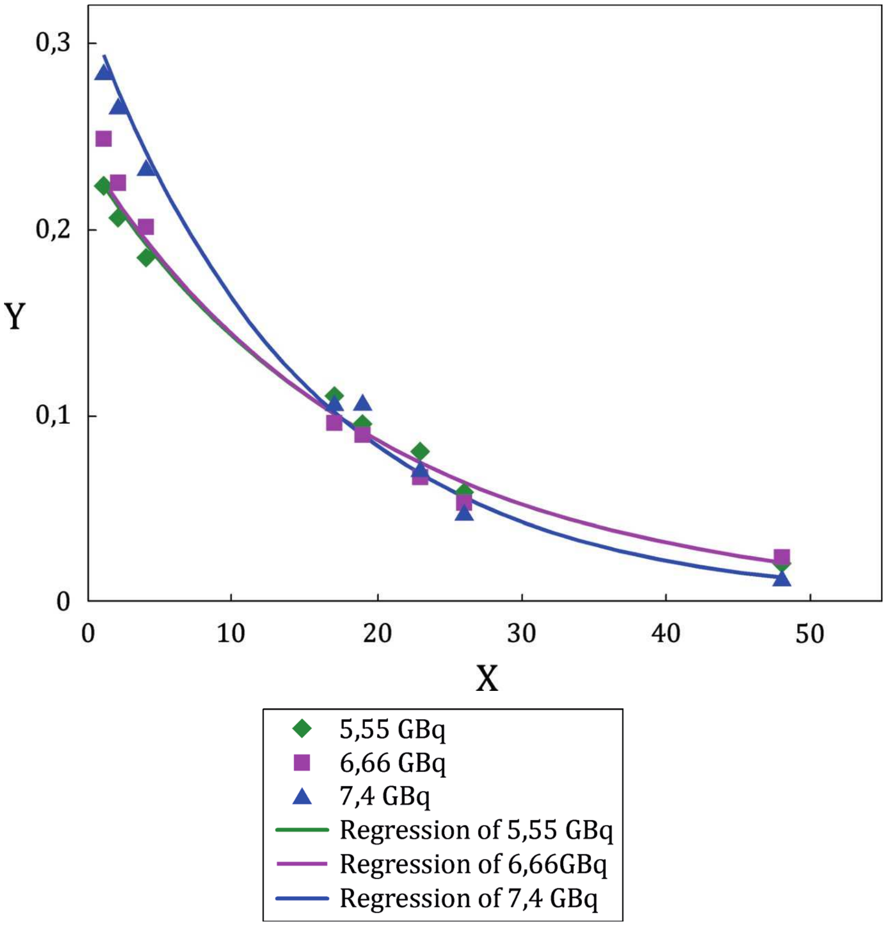
X time (h)

Y dose rate (μSv/h) per MBq

Figure A.5 — Dose rate as a function of time at 10 cm away from the neck of the patient

Essentially, the measurement results for the patients treated with high activities (of 6,66 GBq and 7,40 GBq) at 1 m from the patient showed that the higher the activities administered to the patients were, the less the retentions were. The plot of comparing the change of dose rate as a function of time for the activities of 5,55 GBq, 6,66 GBq and 7,40 GBq are given in Figure A.6.

In Reference [1], a mono-exponential function was used for the determination of ambient dose equivalent rate with a regression analysis instead of the bi-exponential function. For the patients who had 90 % of their thyroid resected through surgery, the radioiodine in the thyroid compartment is not retained or stays over very short periods of time. Thus, the mono-exponential function is enough to describe the behaviour of the radioiodine at the compartment. In other words, the patients with thyroid resection do not follow the ICRP thyroid model[7]. From the derived formula above, the effective half-life of the radioiodine determined at 1 m from the patient was 13,9 h and 10 cm from the patient’s neck was 15,6 h which is much shorter than that for the general public. The difference of the effective half-life between two measurements can be explained by the following argument; in the measurement of ambient dose equivalent rate at 10 cm from the neck of the patient, it is mainly from the radioiodine in thyroid. On the other hand, the dose rate at 1 m from the patient is the sum of radioiodine from thyroid, bladder, kidney and blood, etc. Also, since each organ has a different effective half-life and different metabolism from one another, the dose rate at 1 m from the patient is expected to show a different half-life from that at 10 cm from the neck of the patient. The result in this study is close to that in Reference [2].



**Key**

| | |
|---|---|
| X | time (h) |
| Y | dose rate (μSv/h) per MBq |

Figure A.6 — Comparison of dose rate as a function of time for different activities administered to the patient

**Table A.3 — Standard dose rate 1 m away from the body of the patient after radioiodine administration**

| **h** | **mCi** | **100** | **120** | **150** | **180** | **200** | **220** | **250** | **280** | **300** | **320** | **350** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **GBq** | **3,7** | **4,44** | **5,55** | **6,66** | **7,4** | **8,14** | **9,25** | **10,36** | **11,1** | **11,84** | **12,95** |
| 0 | mSv/h | 0,159 | 0,190 | 0,238 | 0,286 | 0,317 | 0,349 | 0,397 | 0,444 | 0,476 | 0,508 | 0,555 |
| 1 | | 0,151 | 0,181 | 0,226 | 0,272 | 0,302 | 0,332 | 0,377 | 0,422 | 0,453 | 0,483 | 0,528 |
| 2 | | 0,143 | 0,172 | 0,215 | 0,258 | 0,287 | 0,316 | 0,359 | 0,402 | 0,430 | 0,459 | 0,502 |
| 3 | | 0,136 | 0,164 | 0,205 | 0,246 | 0,273 | 0,300 | 0,341 | 0,382 | 0,409 | 0,437 | 0,478 |
| 4 | | 0,130 | 0,156 | 0,195 | 0,234 | 0,260 | 0,286 | 0,325 | 0,363 | 0,389 | 0,415 | 0,454 |
| 5 | | 0,123 | 0,148 | 0,185 | 0,222 | 0,247 | 0,272 | 0,309 | 0,346 | 0,370 | 0,395 | 0,432 |
| 6 | | 0,117 | 0,141 | 0,176 | 0,211 | 0,235 | 0,258 | 0,294 | 0,329 | 0,352 | 0,376 | 0,411 |
| 7 | | 0,112 | 0,134 | 0,168 | 0,201 | 0,223 | 0,246 | 0,279 | 0,313 | 0,335 | 0,357 | 0,391 |
| 8 | | 0,106 | 0,127 | 0,159 | 0,191 | 0,212 | 0,234 | 0,266 | 0,297 | 0,319 | 0,340 | 0,372 |
| 9 | | 0,101 | 0,121 | 0,152 | 0,182 | 0,202 | 0,222 | 0,253 | 0,283 | 0,303 | 0,323 | 0,354 |
| 10 | | 0,096 | 0,115 | 0,144 | 0,173 | 0,192 | 0,211 | 0,240 | 0,269 | 0,288 | 0,308 | 0,336 |
| 11 | | 0,091 | 0,110 | 0,137 | 0,165 | 0,183 | 0,201 | 0,229 | 0,256 | 0,274 | 0,293 | 0,320 |
| 12 | | 0,087 | 0,104 | 0,130 | 0,157 | 0,174 | 0,191 | 0,217 | 0,243 | 0,261 | 0,278 | 0,304 |
| 13 | | 0,083 | 0,099 | 0,124 | 0,149 | 0,165 | 0,182 | 0,207 | 0,232 | 0,248 | 0,265 | 0,289 |
| 14 | | 0,079 | 0,094 | 0,118 | 0,142 | 0,157 | 0,173 | 0,197 | 0,220 | 0,236 | 0,252 | 0,275 |
| 15 | | 0,075 | 0,090 | 0,112 | 0,135 | 0,150 | 0,165 | 0,187 | 0,209 | 0,224 | 0,239 | 0,262 |
| 16 | | 0,071 | 0,085 | 0,107 | 0,128 | 0,142 | 0,157 | 0,178 | 0,199 | 0,213 | 0,228 | 0,249 |
| 17 | | 0,068 | 0,081 | 0,102 | 0,122 | 0,135 | 0,149 | 0,169 | 0,190 | 0,203 | 0,217 | 0,237 |
| 18 | | 0,064 | 0,077 | 0,097 | 0,116 | 0,129 | 0,142 | 0,161 | 0,180 | 0,193 | 0,206 | 0,225 |
| 19 | | 0,061 | 0,073 | 0,092 | 0,110 | 0,122 | 0,135 | 0,153 | 0,171 | 0,184 | 0,196 | 0,214 |
| 20 | | 0,058 | 0,070 | 0,087 | 0,105 | 0,116 | 0,128 | 0,146 | 0,163 | 0,175 | 0,186 | 0,204 |
| 21 | | 0,055 | 0,066 | 0,083 | 0,100 | 0,111 | 0,122 | 0,138 | 0,155 | 0,166 | 0,177 | 0,194 |
| 22 | | 0,053 | 0,063 | 0,079 | 0,095 | 0,105 | 0,116 | 0,132 | 0,148 | 0,158 | 0,169 | 0,184 |
| 23 | | 0,050 | 0,060 | 0,075 | 0,090 | 0,100 | 0,110 | 0,125 | 0,140 | 0,150 | 0,160 | 0,175 |
| 24 | | 0,048 | 0,057 | 0,071 | 0,086 | 0,095 | 0,105 | 0,119 | 0,133 | 0,143 | 0,153 | 0,167 |
| 26 | | 0,043 | 0,052 | 0,065 | 0,078 | 0,086 | 0,095 | 0,108 | 0,121 | 0,129 | 0,138 | 0,151 |
| 28 | | 0,039 | 0,047 | 0,059 | 0,070 | 0,078 | 0,086 | 0,098 | 0,109 | 0,117 | 0,125 | 0,137 |
| 30 | | 0,035 | 0,042 | 0,053 | 0,064 | 0,071 | 0,078 | 0,088 | 0,099 | 0,106 | 0,113 | 0,124 |

**Table A.3** *(continued)*

| **h** | **mCi** | **100** | **120** | **150** | **180** | **200** | **220** | **250** | **280** | **300** | **320** | **350** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **GBq** | **3,7** | **4,44** | **5,55** | **6,66** | **7,4** | **8,14** | **9,25** | **10,36** | **11,1** | **11,84** | **12,95** |
| 32 | mSv/h | 0,032 | 0,038 | 0,048 | 0,057 | 0,064 | 0,070 | 0,080 | 0,089 | 0,096 | 0,102 | 0,112 |
| 34 | | 0,029 | 0,035 | 0,043 | 0,052 | 0,058 | 0,064 | 0,072 | 0,081 | 0,087 | 0,092 | 0,101 |
| 36 | | 0,026 | 0,031 | 0,039 | 0,047 | 0,052 | 0,057 | 0,065 | 0,073 | 0,078 | 0,084 | 0,091 |
| 38 | | 0,024 | 0,028 | 0,035 | 0,043 | 0,047 | 0,052 | 0,059 | 0,066 | 0,071 | 0,076 | 0,083 |
| 40 | | 0,021 | 0,026 | 0,032 | 0,038 | 0,043 | 0,047 | 0,053 | 0,060 | 0,064 | 0,068 | 0,075 |
| 42 | | 0,019 | 0,023 | 0,029 | 0,035 | 0,039 | 0,043 | 0,048 | 0,054 | 0,058 | 0,062 | 0,068 |
| 44 | | 0,017 | 0,021 | 0,026 | 0,031 | 0,035 | 0,038 | 0,044 | 0,049 | 0,052 | 0,056 | 0,061 |
| 46 | | 0,016 | 0,019 | 0,024 | 0,028 | 0,032 | 0,035 | 0,040 | 0,044 | 0,047 | 0,051 | 0,055 |
| 48 | | 0,014 | 0,017 | 0,021 | 0,026 | 0,029 | 0,032 | 0,036 | 0,040 | 0,043 | 0,046 | 0,050 |
| 52 | | 0,012 | 0,014 | 0,018 | 0,021 | 0,023 | 0,026 | 0,029 | 0,033 | 0,035 | 0,038 | 0,041 |
| 56 | | 0,010 | 0,012 | 0,014 | 0,017 | 0,019 | 0,021 | 0,024 | 0,027 | 0,029 | 0,031 | 0,034 |
| 60 | | 0,008 | 0,009 | 0,012 | 0,014 | 0,016 | 0,017 | 0,020 | 0,022 | 0,024 | 0,025 | 0,027 |
| 64 | | 0,006 | 0,008 | 0,010 | 0,012 | 0,013 | 0,014 | 0,016 | 0,018 | 0,019 | 0,021 | 0,022 |
| 68 | | 0,005 | 0,006 | 0,008 | 0,009 | 0,011 | 0,012 | 0,013 | 0,015 | 0,016 | 0,017 | 0,018 |
| 72 | | 0,004 | 0,005 | 0,006 | 0,008 | 0,009 | 0,009 | 0,011 | 0,012 | 0,013 | 0,014 | 0,015 |
| 76 | | 0,004 | 0,004 | 0,005 | 0,006 | 0,007 | 0,008 | 0,009 | 0,010 | 0,011 | 0,011 | 0,012 |
| 80 | | 0,003 | 0,003 | 0,004 | 0,005 | 0,006 | 0,006 | 0,007 | 0,008 | 0,009 | 0,009 | 0,010 |
| 84 | | 0,002 | 0,003 | 0,004 | 0,004 | 0,005 | 0,005 | 0,006 | 0,007 | 0,007 | 0,008 | 0,008 |
| 88 | | 0,002 | 0,002 | 0,003 | 0,003 | 0,004 | 0,004 | 0,005 | 0,005 | 0,006 | 0,006 | 0,007 |
| 92 | | 0,002 | 0,002 | 0,002 | 0,003 | 0,003 | 0,003 | 0,004 | 0,004 | 0,005 | 0,005 | 0,006 |
| 96 | | 0,001 | 0,002 | 0,002 | 0,002 | 0,003 | 0,003 | 0,003 | 0,004 | 0,004 | 0,004 | 0,005 |
| 100 | | 0,001 | 0,001 | 0,002 | 0,002 | 0,002 | 0,002 | 0,003 | 0,003 | 0,003 | 0,003 | 0,004 |
| 104 | | 0,001 | 0,001 | 0,001 | 0,002 | 0,002 | 0,002 | 0,002 | 0,002 | 0,003 | 0,003 | 0,003 |
| 108 | | 0,001 | 0,001 | 0,001 | 0,001 | 0,001 | 0,002 | 0,002 | 0,002 | 0,002 | 0,002 | 0,002 |

**Table A.3** — *(continued)*

| h | mCi | 380 | 400 | 420 | 450 | 480 | 500 | 520 | 550 | 580 | 600 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | GBq | 14,06 | 14,8 | 15,54 | 16,65 | 17,76 | 18,5 | 19,24 | 20,35 | 21,46 | 22,2 |
| 0 | mSv/h | 0,603 | 0,634 | 0,666 | 0,714 | 0,761 | 0,793 | 0,825 | 0,872 | 0,920 | 0,952 |
| 1 | | 0,573 | 0,603 | 0,634 | 0,679 | 0,724 | 0,754 | 0,785 | 0,830 | 0,875 | 0,905 |
| 2 | | 0,545 | 0,574 | 0,603 | 0,646 | 0,689 | 0,717 | 0,746 | 0,789 | 0,832 | 0,861 |
| 3 | | 0,519 | 0,546 | 0,573 | 0,614 | 0,655 | 0,682 | 0,710 | 0,751 | 0,792 | 0,819 |
| 4 | | 0,493 | 0,519 | 0,545 | 0,584 | 0,623 | 0,649 | 0,675 | 0,714 | 0,753 | 0,779 |
| 5 | | 0,469 | 0,494 | 0,519 | 0,556 | 0,593 | 0,617 | 0,642 | 0,679 | 0,716 | 0,741 |
| 6 | | 0,446 | 0,470 | 0,493 | 0,528 | 0,564 | 0,587 | 0,611 | 0,646 | 0,681 | 0,705 |
| 7 | | 0,424 | 0,447 | 0,469 | 0,503 | 0,536 | 0,558 | 0,581 | 0,614 | 0,648 | 0,670 |
| 8 | | 0,404 | 0,425 | 0,446 | 0,478 | 0,510 | 0,531 | 0,552 | 0,584 | 0,616 | 0,637 |
| 9 | | 0,384 | 0,404 | 0,424 | 0,455 | 0,485 | 0,505 | 0,525 | 0,556 | 0,586 | 0,606 |
| 10 | | 0,365 | 0,384 | 0,404 | 0,433 | 0,461 | 0,481 | 0,500 | 0,529 | 0,557 | 0,577 |
| 11 | | 0,347 | 0,366 | 0,384 | 0,411 | 0,439 | 0,457 | 0,475 | 0,503 | 0,530 | 0,548 |
| 12 | | 0,330 | 0,348 | 0,365 | 0,391 | 0,417 | 0,435 | 0,452 | 0,478 | 0,504 | 0,522 |
| 13 | | 0,314 | 0,331 | 0,347 | 0,372 | 0,397 | 0,413 | 0,430 | 0,455 | 0,480 | 0,496 |
| 14 | | 0,299 | 0,315 | 0,330 | 0,354 | 0,378 | 0,393 | 0,409 | 0,433 | 0,456 | 0,472 |
| 15 | | 0,284 | 0,299 | 0,314 | 0,337 | 0,359 | 0,374 | 0,389 | 0,411 | 0,434 | 0,449 |
| 16 | | 0,270 | 0,285 | 0,299 | 0,320 | 0,342 | 0,356 | 0,370 | 0,391 | 0,413 | 0,427 |
| 17 | | 0,257 | 0,271 | 0,284 | 0,305 | 0,325 | 0,338 | 0,352 | 0,372 | 0,393 | 0,406 |
| 18 | | 0,245 | 0,257 | 0,270 | 0,290 | 0,309 | 0,322 | 0,335 | 0,354 | 0,373 | 0,386 |
| 19 | | 0,233 | 0,245 | 0,257 | 0,276 | 0,294 | 0,306 | 0,318 | 0,337 | 0,355 | 0,367 |
| 20 | | 0,221 | 0,233 | 0,245 | 0,262 | 0,280 | 0,291 | 0,303 | 0,320 | 0,338 | 0,349 |
| 21 | | 0,210 | 0,222 | 0,233 | 0,249 | 0,266 | 0,277 | 0,288 | 0,305 | 0,321 | 0,332 |
| 22 | | 0,200 | 0,211 | 0,221 | 0,237 | 0,253 | 0,263 | 0,274 | 0,290 | 0,306 | 0,316 |
| 23 | | 0,190 | 0,200 | 0,210 | 0,225 | 0,241 | 0,251 | 0,261 | 0,276 | 0,291 | 0,301 |
| 24 | | 0,181 | 0,191 | 0,200 | 0,214 | 0,229 | 0,238 | 0,248 | 0,262 | 0,276 | 0,286 |
| 26 | | 0,164 | 0,172 | 0,181 | 0,194 | 0,207 | 0,216 | 0,224 | 0,237 | 0,250 | 0,259 |
| 28 | | 0,148 | 0,156 | 0,164 | 0,176 | 0,187 | 0,195 | 0,203 | 0,215 | 0,226 | 0,234 |
| 30 | | 0,134 | 0,141 | 0,148 | 0,159 | 0,169 | 0,176 | 0,183 | 0,194 | 0,205 | 0,212 |

**Table A.3** *(continued)*

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | mSv/h | 0,121 | 0,128 | 0,134 | 0,144 | 0,153 | 0,160 | 0,166 | 0,176 | 0,185 | 0,192 |
| 34 | | 0,110 | 0,116 | 0,121 | 0,130 | 0,139 | 0,144 | 0,150 | 0,159 | 0,167 | 0,173 |
| 36 | | 0,099 | 0,105 | 0,110 | 0,118 | 0,125 | 0,131 | 0,136 | 0,144 | 0,152 | 0,157 |
| 38 | | 0,090 | 0,095 | 0,099 | 0,106 | 0,113 | 0,118 | 0,123 | 0,130 | 0,137 | 0,142 |
| 40 | | 0,081 | 0,086 | 0,090 | 0,096 | 0,103 | 0,107 | 0,111 | 0,118 | 0,124 | 0,128 |
| 42 | | 0,074 | 0,077 | 0,081 | 0,087 | 0,093 | 0,097 | 0,101 | 0,106 | 0,112 | 0,116 |
| 44 | | 0,066 | 0,070 | 0,073 | 0,079 | 0,084 | 0,087 | 0,091 | 0,096 | 0,101 | 0,105 |
| 46 | | 0,060 | 0,063 | 0,066 | 0,071 | 0,076 | 0,079 | 0,082 | 0,087 | 0,092 | 0,095 |
| 48 | | 0,054 | 0,057 | 0,060 | 0,064 | 0,069 | 0,072 | 0,074 | 0,079 | 0,083 | 0,086 |
| 52 | | 0,045 | 0,047 | 0,049 | 0,053 | 0,056 | 0,059 | 0,061 | 0,064 | 0,068 | 0,070 |
| 56 | | 0,036 | 0,038 | 0,040 | 0,043 | 0,046 | 0,048 | 0,050 | 0,053 | 0,056 | 0,058 |
| 60 | | 0,030 | 0,031 | 0,033 | 0,035 | 0,038 | 0,039 | 0,041 | 0,043 | 0,046 | 0,047 |
| 64 | | 0,024 | 0,026 | 0,027 | 0,029 | 0,031 | 0,032 | 0,033 | 0,035 | 0,037 | 0,039 |
| 68 | | 0,020 | 0,021 | 0,022 | 0,024 | 0,025 | 0,026 | 0,027 | 0,029 | 0,030 | 0,032 |
| 72 | | 0,016 | 0,017 | 0,018 | 0,019 | 0,021 | 0,022 | 0,022 | 0,024 | 0,025 | 0,026 |
| 76 | | 0,013 | 0,014 | 0,015 | 0,016 | 0,017 | 0,018 | 0,018 | 0,019 | 0,020 | 0,021 |
| 80 | | 0,011 | 0,012 | 0,012 | 0,013 | 0,014 | 0,014 | 0,015 | 0,016 | 0,017 | 0,017 |
| 84 | | 0,009 | 0,009 | 0,010 | 0,011 | 0,011 | 0,012 | 0,012 | 0,013 | 0,014 | 0,014 |
| 88 | | 0,007 | 0,008 | 0,008 | 0,009 | 0,009 | 0,010 | 0,010 | 0,011 | 0,011 | 0,012 |
| 92 | | 0,006 | 0,006 | 0,007 | 0,007 | 0,008 | 0,008 | 0,008 | 0,009 | 0,009 | 0,009 |
| 96 | | 0,005 | 0,005 | 0,005 | 0,006 | 0,006 | 0,006 | 0,007 | 0,007 | 0,007 | 0,008 |
| 100 | | 0,004 | 0,004 | 0,004 | 0,005 | 0,005 | 0,005 | 0,006 | 0,006 | 0,006 | 0,006 |
| 104 | | 0,003 | 0,003 | 0,004 | 0,004 | 0,004 | 0,004 | 0,005 | 0,005 | 0,005 | 0,005 |
| 108 | | 0,003 | 0,003 | 0,003 | 0,003 | 0,003 | 0,004 | 0,004 | 0,004 | 0,004 | 0,004 |

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